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THE IMPACTS OF INDUSTRIAL ROBOTS

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The Impacts of Industrial Robots

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Abstract: This report briefly describes robot technology and goes into more depth about where robots are used, and some of the anticipated social and economic impacts of their use. A number of short term transitional issues, including problems of potential displacement, are discussed. The ways in which robots may impact the economics of batch production are described. A framework for analyzing the impacts of robotics on ecnomywide economic growth and employment is presented. Human resource policy issues are discussed. A chronology of robotics technology is also given.

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1 What Are Industrial Robots?

Industrial robots are machine tools. They are not human-like androids which can stroll around and converse like the famed R2D2 and C3PO of *Star Wars*. More realistically, they are programmable manipulators which can move parts or tools through a prespecified sequence of motions. Reprogrammability means that the robot's actions can be modified by changing control settings, without changing the hardware. They combine some attributes of traditional machine tools as well as attributes of machine tool operators. Like a machine tool, the robot can repeat the same task for prolonged periods with great precision. Like an operator, it is flexible enough to be taught to do a new task, and it can use accessory tools to extend its range of physical capabilities.

Robots are valued in industry for the usual qualities of machines: untiring availability, predictability, reliability, precision and (relative) imperviousness to hostile environments. They do not, as yet, possess several important capabilities which come naturally to humans: the ability to react to unforeseen circumstances or changing environments, and the ability to improve performance based on prior experience. State-of-the art robots (mostly in research labs) do have crude senses of "sight" and "touch", and limited capability to coordinate their manipulators with sensory input. Because of current limitations, today's robots are usefully employed in highly structured industrial environments where practically all of the variability and decision making can be engineered out of the workplace. Existing uses of industrial robots all involve repetitive preprogrammable tasks such as spot welding, spray painting, palletizing, and the loading and unloading of many types of metal forming and metal cutting machines. The next generation of sensor based robots will be able to perform a broader range of tasks under less structured conditions, in addition to becoming cheaper and easier to use. Expected uses of robots with vision and improved feedback control will include inspection, assembly, heat treatment, grinding and buffing, and electroplating.

Eventually, many of the "hands on" tasks performed by production workers on the factory floor will be done by robots in computer controlled manufacturing systems. Programmable automation is beginning to replace the current generation of manually controlled machines. This transition will undoubtedly continue for many decades. There is a potential for significantly improving the productivity of our manufacturing sector, and increasing the wealth producing potential of the economy as a whole. We also face significant social impacts, such as the short term prospect of technological displacement, and the longer term prospects of basic structural shifts in the economy.

2 Chronology of Robot Developments

The term "robot" allegedly stems from the Czeck word "robotnik", meaning serf. It was first introduced into the popular language by Carel Capek, a Czeck Playwright, in R.U.R. The concept of programmable machinery, however, dates back much earlier, to the 18 th century, when the Frenchman Bouchon, Vacaunson,Basile, Falcon and Jacquard developed mechanical looms which were controlled by punch cards. Spencer's Automat, a cam programmable lathe used for producing screws, nuts, and gears, was controlled by fitting guides to the end of a rotating drum in the mid 1870's. Since then, mechanical controls have proliferated in the machine tool industry.

Mechanical manipulators also have a long history. In 1892, Seward Babbitt, of Pittsburgh, patented a rotary crane with a motorized gripper for removing ingots out of furnaces. The first jointed mechanical arm which could could play back a series of motions was developed by Pollard in 1938. The machine was specialized for spray painting. The first *general purpose* playback unit for controlling machines was developed by George Devol in 1946. He licensed the device to Remington Rand, who intended to use it for the Univac Computer, which was just developed. The controller was not fast enough for the desired purpose, and the patent was returned to Devol. In 1954, Devol developed the first general purpose manipulator with a playback memory and point-to-point control. The patent for this *Programmed Article Transfer* was issued in 1961. The patent states, *Universal Automation, or "Unimation", is a term that may well characterize the general object of this invention.* Devol's early patents were sold to Condec, and formed base for Condec's robot division, Unimation, Inc. In the period between 1954 and 1963, Devol and several others patented the major features of the first generation of robots.

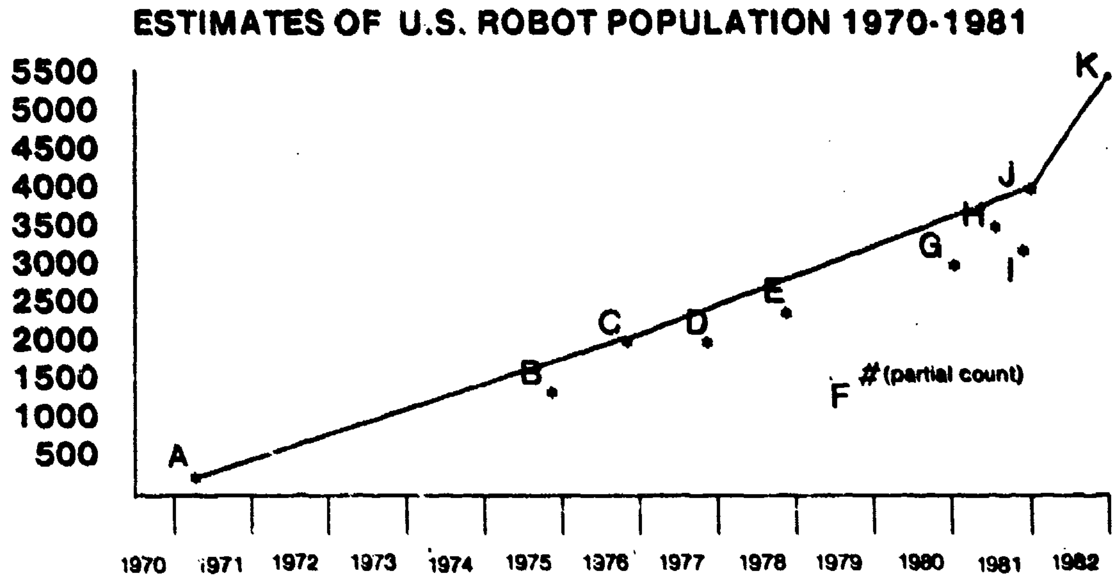
Early robots had computer like functions, such as memory, but were made up of electronic logic components "hardwired" to perform a specific set of tasks. Electronic controls were used to essentially duplicate the functions of other "hard automated" control functions. Robots controlled by general purpose computers were developed in the early 1970's. The first mini computer controlled was commercialized in 1974 by Cincinnati Milacron. Microprocessor controlled robots followed several years later. The computer controlled, or "soft wired" robot, is far more powerful than a machine with specialized electronic logic circuts. It can work in several coordinate systems, be programmed "off-line", interface with sensors, and so on. Computer controlled robots are now becoming very specialized peripheral features of a general purpose computer. A partial, and still preliminary chronology of significant developments in robotics is given in the appendix.

3 Robot Use in the United States

Industrial robots in the United States are undergoing a virtual population explosion. Their numbers have increased from 200 in 1970 to 4,000 by 1980, and to nearly 5,500 by the end Of 1981. Industry's experience with robots, however, has so far been largely confined to a relatively small number of firms. At the beginning of 1981, almost 30 percent of the U.S. robot population belonged to only six firms, three of which were in the auto industry. By all indications, the real impact of robotics has just begun to be felt.

The Japanese have more experience in robot applications, even though robots were originally developed, and first applied in the United States. According to Paul Aron (Aron,81), as of the beginning of 1981, there were over 11,000 machines in Japan which match the definition of industrial robots applied in the United States. Comparing this count to our US population estimates, the Japanese have nearly three times as many industrial robots installed and operating as the United States.[1]

[1] Occasional claims that Japan has many times more robots than the U.S. stem from a difference in definition. The Japanese include manual manipulators, and fixed sequence machines in their total robot count, whereas the U.S. does not. According to Aron, there were over 65,000 of these manual and fixed sequence machines in Japan as of the beginning of 1981



Point	# of Robots	Date	Source
A	200	1970 (April)	Engelberger, First National Symposium on Industrial Robots , 1970
B	1200	1974 (Dec.)	Frost and Sullivan, U.S. Industrial Robot Market, 1974
C	2000	1975 (Dec.)	Frost and Sullivan, The Industrial Robot Market in Europe, 1975
D	2000	1976 (Dec.)	Eikonix Technology Assessment, 1979
E	2400	1977 (Dec.)	Eikonix Technology Assessment, 1979
F	1600	1978 (Dec.)	American Machinist 12th Inventory, 1978
G	3000	1980 (Jan.)	Walt Weisel, Prab Conveyors
H	3500	1980 (June)	Business Week, Verfied by Cincinnati Milacron
I	3200	1980 (Dec.)	General Motors Technical Staff, (Bache,Shields estimate)
J	4000	1980 (Dec.)	Walt Weisel, Prab Conveyors
K	5500	1981 (Dec)	Seiko Inc., Marketing Dept.

Figure 1: Estimates of U.S. Robot Population, 1970-1981

4 Robot Technology- A Brief Review

Existing industrial robots, are essentially, programmable multi-jointed arms with gripers or tool-holders at the end, capable of moving a tool or workpiece to a pre-specified sequence of points, or along a specified path within the arms reach and transmitting precisely-defined energy flows (e.g. forces and torques) or objects to these points. Capabilities of commercially available robots, and capabilities under development for future robots are listed in Table 1.[2]

Their are four general architectural types of kinematic and structural designs distinguishable in terms of coordinate systems:

Cartesian (rectilinear)	(X,Y,Z)
Cylindrical	(r,Z,θ)
Polar	(r,φ,θ)
Revolute (polar articulated)	(ω,φ,θ)

Each of these systems has three degrees of freedom, sufficient for the arm to reach any point within a volume of space defined by the maximum extension of the arm.[3] Of these types, the anthropomorphic revolute (or polar articulated) architecture, requiring only cylindrical couplings, offers comparatively large working volume with minimal spacial intrusion and good ability to avoid obstacles along the position path. The chief disadvantage of polar architectures has been that servo controls for continuous path operation are more sophisticated than controls required for the other architectures. However, recent advances in computer processing power have effectively eliminated this drawback. For this reason, cartesian and cylindrical architectures are likely to assume reduced importance in the future, except where exceptional positional accuracy is needed.

As three degrees of freedom are required to reach any point within the working volume, three additional degrees of freedom are required to deliver the tool or workpiece in any arbitrary orientation. This may not be necessary in some cases, e.g. if the workpiece is cylindrical or spherical. Most robots have some type of articulated wrist, giving them the additional degrees of freedom as needed.

The performance characteristics of robots without sensory feedback can be summerized under four headings:

- **manipulability of the payload**

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[2] Many of the capabilities listed as being "sought for the future" have already gone through one or more generations of development.

[3] Most robots have only one arm, however, multiarm robots for welding and assembly are now available from several manufacturers.

ROBOT CAPABILITIES

	Commercially Available Capabilities (1980)	Capabilities Sought for the Future
Learning	• online programming via teach/playback modes • teaching in multiple coordinates • local and library memories of any size	• general purpose robot programming languages • off line programming • "learning" with experience • "world model" of working environment
Decision Making	• program selection by random stimuli • computer interpretation of sensory data	
Sensing	• computer interfacing • 2-D vision with binary recognition • force/torque sensing • limited speech input	• positional sensing • 3-D vision with grey levels and color • tactile sensing • voice communication • improved processing of sensory inputs • coordination of multiple sensory inputs and control
Manipulation	• six infinitely controllable articulations between base and gripper • point to point control • continuous path control • position accuracy repeatable to 0.3mm • handles up to 150 kilos	• miniture manipulators • greater position accuracy • greater dynamic control • general purpose hands • multiple hand-to-hand coordination
Mobility	• synchronization with moving workpieces	• programmable omni directional mobile bases • self navigating mobile bases • "walking" robots
Reliability	• 400 hours for mean time between failure	• self diagnostic fault tracing

Table 1: Robot Capabilities

- **reliability**
- **programmability**
- **mobility of the robot as a whole**

More detailed discussions of these characteristics and extensive references are found in (Toepperwein,1980) and (Engelberger,1980). Temporary limitations of robots relate to the speed of the arm, the amount of force or payload it can deliver, the precision of the motions, the ease of programmability and the complexity of sequence of actions it can be instructed to do. There are significant tradeoffs between the various performance characteristics. Extreme accuracy is available from robots with only three or four degrees of freedom,a very small payload, and a relatively tiny working volume. Such robots may be appropriate for limited operations with very small parts, such as assembling watches or cameras. On the other hand, robots capable of handling large payloads over significant working volumes do not, as a rule, achieve very precise positional accuracy.

Present manipulators are still far inferior to human arms, and are unsatisfactory for many applications, due to limitations on speed, accuracy, and versatility. Transmission mechanisms, such as gear trains, lead screws, steel belts, chains and linkages used to transmit power from motors to the load constrain performance capabilities. New robot designs,.such as the direct drive manipulator developed at Carnegie-Mellon (See Asada,81), make it possible to remove all the transmission mechanisms between motors and the load, and pave the way for a new generation of light weight, high performance robot arms.

The more fundamental limitation on present day robot capabilities relates to the need for pre-specification of the task in complete detail. Most tasks in the real world cannot be pre-specified to the required degree, but require adjustments and modifications as the task proceeds. Picking standard parts from a bin is trivially easy for humans and exceeding difficult for a robot. The same applies to cutting logs or fitting pieces of cloth together. The robot must sense the appropriate attributes of the workpieces as the operation proceeds, and make corrective maneuvers as needed. It must be able to recognize when the workpiece is damaged and should be removed from the line, and recognize when the desired result has been achieved. These are major challenges to the state of the art.

Capabilities necessary to overcome the difficulties of coping with non-standard orientations and variable workpiece attitudes can be summerized under two headings:

- sensing
- learning and planning

Robot sensors are divided into three major categories, following (Raibert, 1981), in Table 2. While the range of possible sensory inputs is quite large, the problem of interpreting the sensory signals by the robot's controlling "brain" remains as a separate dimension. The transducers respond to external stimulation, and provide a stream of input data which is transported to the robot's control system via communication devices. However,the information cannot be used for purposes of decision making until computational elements filter, enhance, interpret, and make perceptions on the raw data. Very few sensors have been used in industrial applications to date, but industry and research labs are actively studying new sensing devices and algorithms for interpreting sensed information.

Table 2: Overview of Robotic Sensors

Internal Sensing	Sensors to measure internal variables important to the control of a robotic mechanism, such as the position and velocity of joints in a manipulator or in a locomotion system, or internal forces, temperatures and pressures. There is no direct interaction between the sensor and the outside environment. Some type of internal sensing is found in every type of robotic mechanism.
Contact Sensing	Sensors measuring touch, force, pressure, slip, or any type of tactile or force input to monitor the interactions between the robot and its environment. Small deviations in position which are normally hard to measure can result in very large forces which are easy to measure.
In tactile or touch	sensing, switches, piezoelectric devices, pressure sensitive plastics, and strain gauges are used to measure very small forces at a number of points on the robot's end effector. Except for the simplest on-off devices, tactile sensors are not yet found on commercially available robots.
Forces are sensed	by using strain gauges or piezoelectric sensors to measure all forces and torques transmitted from the robot's end effector to the rest of the manipulator. Forces can also be measured at the actuators.
Range Sensing	Sensors which measure the interactions of the robot and its environment without any form of mechanical contact. Vision, laser ranging, proximity sensing, sonar, and radar sense the environment by collecting and measuring reflected energy. In computer vision systems, TV cameras are interfaced to computer systems to analyze what is seen, and to act upon this information. Proximity sensors radiate light over small distances and measure the reflected light from a specific volume. Laser rangefinding is used to analyze a three dimensional geometry. A steerable laser transmits a spot of light toward the region of interest. The time-of-flight devices measure the time it takes for the spot to return to determine the distance to the reflecting object. Triangulation devices displace the receiver from the source so that the horizontal location of the reflected spot indicates its distances.

Adapted from:
Marc Raibert, *Robotics in Principle and Practice--A Tutorial*,
The Robotics Institute, Carnegie Mellon University, 1981.

Computer vision has received the most research attention to date of all the range sensing techniques. Vision systems which could determine the range and shape of an object using the "structured light" technique were first developed in 1971. In this approach to robotic vision, light is projected onto the object in a controlled manner. The range is determined by triangulation, and the shape is inferred form the intersection of the object and the beam. There are several commercially available systems using the structured light technique. These systems are used to inspect, count, locate, and orient parts, as well as to guide (servo) a manipulator to an object in real time. More advanced vision systems which have the capability to use grey scales , stereo ranging and three dimensional modelling, and which can be programmed to recognize shapes, are approaching commercialization.

Learning capabilities relate to the creation and modification of an instructional program on-line, based on a goal statement and sensory input data. Researchers recognize the need for a software interface to achieve "learning by experience", and high level planning. It is very easy to tell people what to do, and have them figure out how to do it. Given the instruction, " Put the nut on the screw", any normal child could accomplish the task without further detail. But today's robot would require ever each and every detail to be specified in great detail, from how to hold the screw and the nut, to finding collision free paths. Robot programming languages can , to varying degrees, plan simple tasks given instructions. These programming languages are classified in terms of the amount of knowledge and reasoning power they require of the robot. *Explicitly- programmed* languages require the user to specify manipulator positions and trajectories. *World-modelling* languages use very simple instructions merely to specify what is to happen. Manipulator positions and trajectories are generated automatically.

Clearly, robot programming languages can only be used with robots that are controlled by a general purpose, programmable computer. As of today, very few of the robots currently installed in the US, and throughout the world are actually computer controlled.

5 Robot Applications in Standard Industrial Tasks

A convenient classification of factory tasks robots are capable of doing, , following (De Gregorio, 1980), is given in Table 3. Robots have initially had the greatest success to date in spot welding applications, followed the loading and unloading of machine tools, forges, die casting machines and stamping presses, as well as spray painting, palletizing, and heat treating. Even in these established applications areas, many practical problems remain to be solved.

Metal cutting machine tools can be loaded and unloaded by hand, by robots or by integrated devices fed by automatic transfer lines, as in automobile engine plants. The role of robots here will be limited to cases where automatic transfer lines are inappropriate, because a variety of different parts must be processed, but batch sizes are large enough to justify numerically controlled machine tools, fed by robots. Because commercially robots cannot yet handle nonoriented parts, the most successful present application is one where the robot unloads one machine and transfers the part to another machine. The operational linkages between robots and other machines is discussed later on.

A vital task that has attracted much research attention is parts assembly. With minor exceptions,

Table 3: Classification of Industrial Robot Tasks

1. PURE DISPLACEMENT
   a. Loading/Unloading of Machines:
      i. machine tools: deburring, drilling, grinding,milling,routing machines
      ii. plastic materials forming and injection machines
      iii. metal die casting machines
      iv. hot forging and stamping machines
      v. cold forging machines
      vi. cold sheet stamping machines
      vii. furnaces
      viii. heat treating machines
      ix. foundry equipment
   b. Parts Manipulation
      i. packing
      ii. sorting
      iii. conveying
      iv. orienting
   c. Palletizing
2. DISPLACEMENT AND PROCESSING
   a. Spot Welding
   b. Continous Welding
   c. Mechanical/Electrical Parts Assembly
   d. Spray Painting
   e. Cabling
   f. Cutting
   g. Other Processing Operations With Portable Tools.
3. DISPLACEMENT AND INSPECTION
   a. Dimensional Control
   b. Other Quality Control Functions

Source: G.M. de Gregorio,Technological Forecasting of Industrial Robotics, Proceedings of the 10 th International Symposium on Industrial Robots, 1980, Milan, Italy.

existing assembly line jobs cannot be efficiently accomplished by present-day robots for several reasons, including inability to recognize and pick up a desired part from a mixed collection, lack of a sufficiently flexible multi-purpose gripper, and the lack of high level programming languages to reduce time consuming and expensive set-up procedures. These limitations can be removed, to some extent, in newly designed plants where all parts are palletized, or otherwise pre-oriented as they enter from the outside, and handled automatically thereafter. The other, and more general approach to the problem is to develop robots with vision,and tactile feedback, or other forms of contact or range sensing, and that can be programmed "off-line", using high level languages. Another factor which has emerged through research is that assembly tasks often must be restructured to exploit the capabilities of the robot.

6 The Role of Robotics in Manufacturing

The basic production processes employed in industry today are distinguished by the *batch size*- or the length of the production run. The basic production processes are outlined in Figure 2. The distribution of value added in the engineering industries-- industries producing metal, electrical, and electronic goods-- is shown in Figure 3. Contrary to popular belief, American manufacturing industry is *not* primarily involved in mass production. According to these widely publicised figures, published last year by the Machine Tool Task Force, between 50 - 75 % of the dollar value of manufactured goods in the engineering industries are *batch* produced. Our own estimates on the distribution of valued added by batch and mass production for all manufacturing are shown in Figure 4. Our preliminary estimates are consistant with the earlier figures. The bulk of value added in durable goods industries (which includes the engineering industries) is derived from batch produced goods. Our figures suggest, however, that when all manufacturing is considered, over half of value added originates from mass produced goods.[4] Acknowledging inaccuracies in our estimates, it seems clear that a large fraction of all manufactured goods are batch produced, and industry specialist are suggesting that this fraction will increase.

In batch production, operations are done repetitively, but only for periods of hours or days, or maybe weeks. There is a need to perform efficiently, since a sizable number of copies of each product are made. There is also a need for flexibility, since the machine must be reconfigured for another product at the end of the run. Only "flexible" types of automation-- multipurpose, computer controlled machines which are easily reprogrammed-- such as robots and numerically controlled machine tools are suitable for batch production.

Robots are not yet cost effective in most custom applications because in such cases, a large fraction of the labor time is spent <u>setting up</u> the machines. This still requires the active involvement of a skilled machinist. Also, programming time would typically exceed operation time. For one-of-a kind and prototype products, it is usually easier for a skilled machinist to make the piece then to figure out how to do it again with a robot. However, developments in computer aided design, such as the

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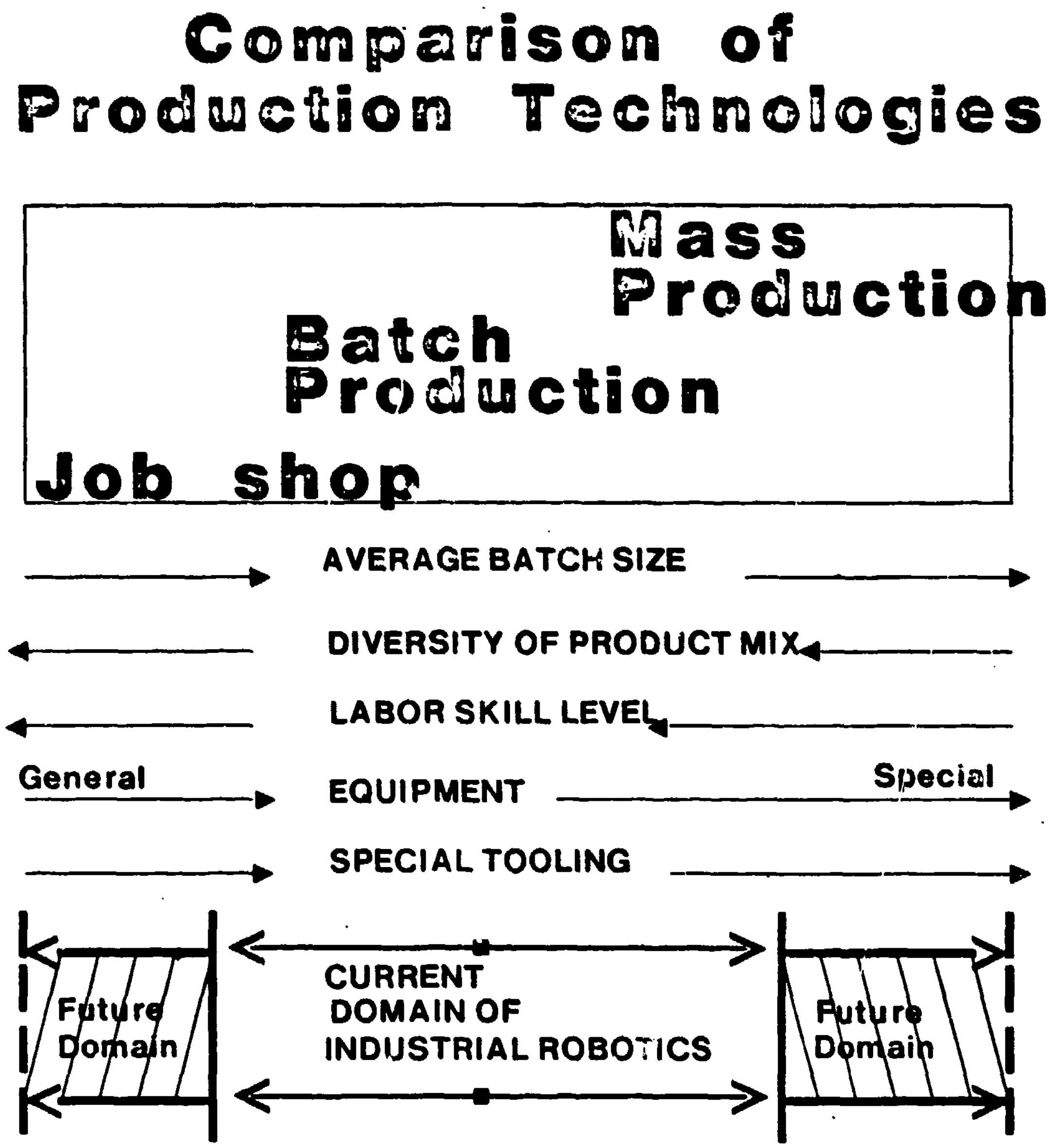
[4] There is no precise way for identifying industries as batch or mass producers. These estimates are based on our own judgement and experience. The difference between batch and mass production is growing less distinct, and, as as machiney becomes more flexible, the distinction will become indistinguishably blurry.



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Automation,Production Systems, and Computer Aided Manufacturing

Figure 2: Comparison of Production Technologies

Distribution of Dollar Value of Manufactured Goods By Batch Size

(IN THE ENGINEERING INDUSTRIES)

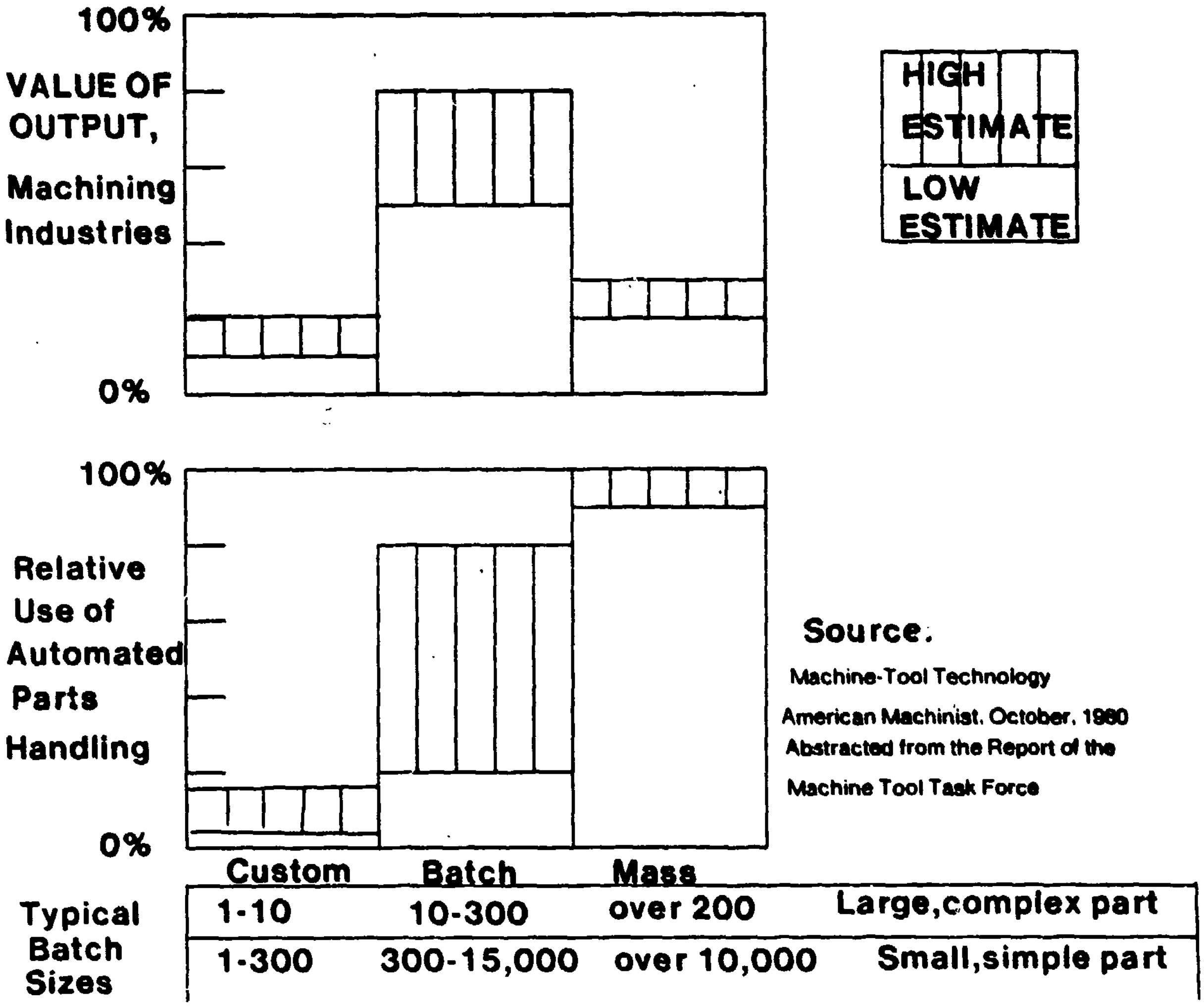
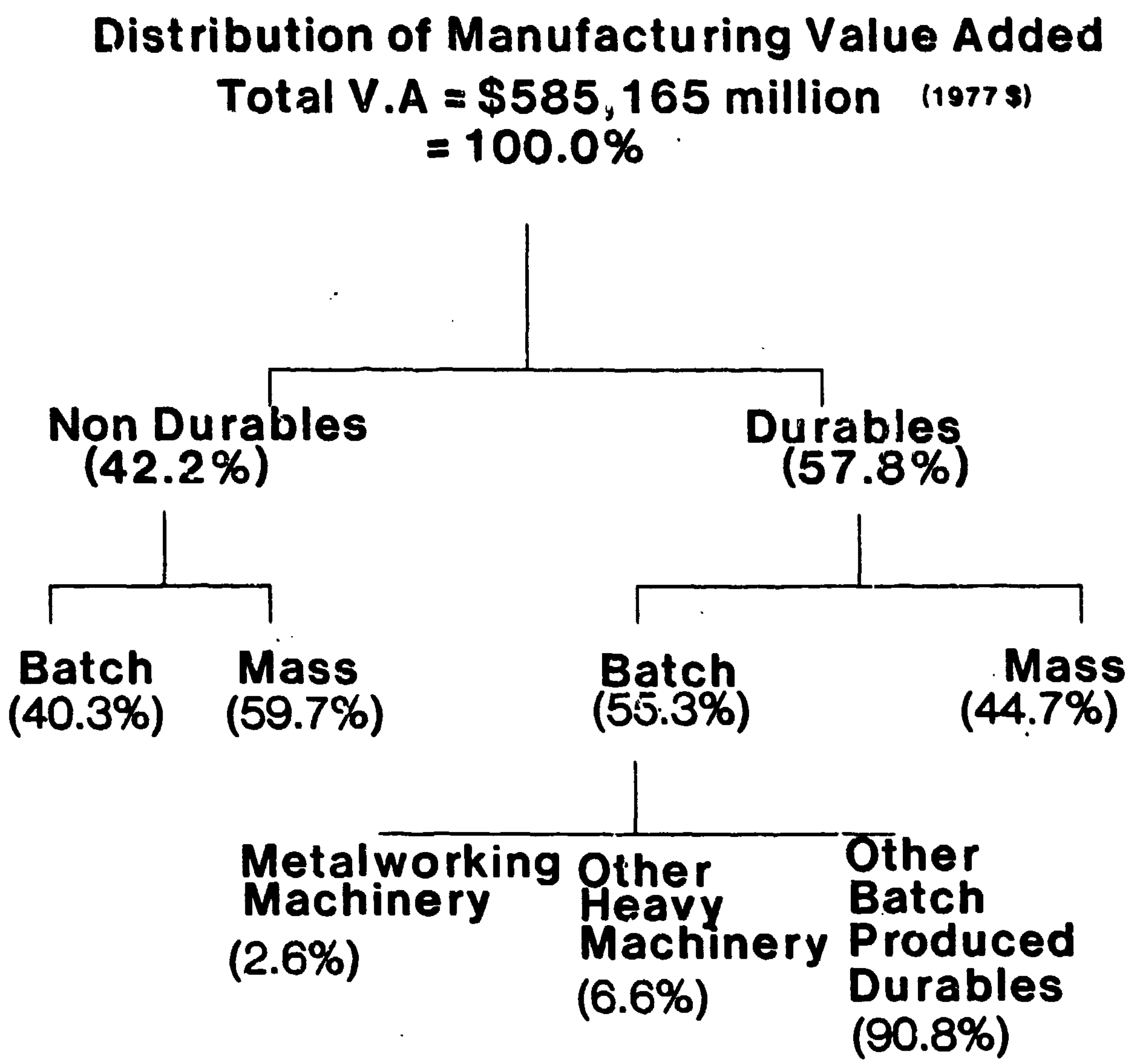


Figure 3: Distribution of Value Added in the Engineering Industries by Batch Size



Figures for Value Added: 1977 Census of Manufacturing
Grouping of Batch and Mass Production Industries: Ayres&Miller

Figure 4: Distribution of Value Added in Manufacturing by Batch and Mass Production

automatic generation of parts programs from design drawings, are making robotics more applicable in small batch and custom operations.

Robots are not generally cost effec: e in most mass production applications, either, because specialized mass production machinery can usually perform the operations more efficiently. Cycle times for today's robots are comparable to human cycle times, making it difficult from them to be used in high speed work. Mass production machinery, or *hard automation*, on the other hand, is highly specialized to repeat a fixed sequence of operations at high speeds for very long periods of time. Auto engines and transmissions are manufactured in this way. However,it always difficult and expensive--if not impossible-- to reconfigure the hard automated system for another product. It is usually cheaper to scrap the machinery, and rebuild the system from scratch. As cycle times are reduced, and systems designs improve, robots will become more widely used in high speed, large volume operations.

The important characteristics of the specialized "hard automated " transter lines used to produce automobile engines are described in (Taylor, 1979):

> ...The system is based on a large volume of repetitive but complex machining operations. Because of precision tolerance requirements in addition to volume production, large manufacturing capital cost are involved. Except over a very limited range, little flexibility is inherent in the system to accommodate change. Only a single product is made with very limited or minor variations, but under a manufacturing environment that is engineered to turn out the product in large quantities at minimum cost.

The last sentence reveals the inherent limitations of "hard automation" technology. It is the cheapest method of production precisely because each element in the system is dedicated to a single function, for which it is optimized. But the entire plant is virtually a single specialized machine capable of producing only a single product. Hard automation is also very expensive to install because each application is custom-made and ,therefore, quite labor intensive.

Most of the batch production industries, and potential robot users, fall within a group of industries that are commonly referred to as the *metalworking sector*. This sector includes the following industries (followed by their Standard Industrial Classification Code):[5]

- Fabricated Metals (SIC 34)
- Machinery , except Electrical (SIC 35)
- Electrical and Electronic Equipment (SIC 36)
- Transportation Equipment (SIC 37)

According to The 12 th American Machinist inventory of machine tools in the metalworking sector taken between 1976 and 1978, less then three percent of the three million machines in these

[5] A broader definition of the metalworking sector would include Furniture and Fixtures (SIC 25) , Primary Metals (SIC 33) and Precision Instruments (SIC 38). Throughout this paper. we restrict our definition of the metalworking sector to SIC codes 34-37

industries were numerically controlled. According to estimates by several robot manufacturers, there are roughly 5000 robots operating throughout all of U.S industry as of mid 1981, of which around 80% are in the metalworking sector. This means there is roughly one robot for every 1300 production workers in the metalworking industries, or even more surprising, less then one robot for every 3000 production workers throughout all manufacturing.

Table 4: Ratio of Production Workers to Robots, Mid 1981

	METALWORKING (SIC 34-37)	ALL MANUFACTURING (SIC 20-37)
Estimated number of robots, June,1980	80 % of 5000 = 4000	5000
Number of Production Workers (Annual Averages for 1980)	5,387,000	14,277,000
Workers/Robots	1347	2856

Sources:
Robot Population: CMU Robotics Survey, April, 1981.
Employment: Employment and Earnings, March, 1981. Table B-2.
Bureau of Labor Statistics

We see that despite the improvements in computer controlled machine tools and robots over the past 20 years the production technology in most batch production factories, and in practically all job shops is still labor intensive and manually controlled . Thus, a large share of all manufacturing is performed with labor intensive methods involving manual control.

It is no wonder that the United States industry is having problems controlling cost, maintaining high standards of product quality and improving productivity. Batch production makes it difficult to optimize machine tool and/or labor utilization. The greater the variability of the product mix, the harder it is to control the cost and quality standards for a particular product. From a producers point of view, a variable product mix, and the capability to manufacture new products is highly desirable. On the other hand, to improve productivity the flows of inputs and outputs must be more tightly (but flexibly) coordinated and controlled. One of the primary reasons for performance problems in the U.S.manufacturing sector is international competitions is forcing producers to simultaneously increase *both* product variety and product quality. These simultaneous but mutually interfering requirements are pushing existing production technologies and management techniques beyond their current capabilities.

7 Integration of Robots into CAD/CAM Systems in Metalworking

Robots are considered a "flexible" technology because their reprogrammability allows them to be quickly adapted to changes in the production process. Robot flexibility has two aspects. First, a robot may be programmed to perform the same task on a variety of different work pieces. This type of application is commonly seen in several areas such as spot welding. A second type of flexibility involves shifting an idle robot to an entirely new task. Our interviews with industrial users suggest that a particular robot is most often specialized to a particular application, partially due to mobility constraints. Even though programmable machines are not, as yet, fully exploited for their full range of flexibility, it is widely acknowledged in engineering circles that flexible automation--or flexible computerized manufacturing systems (FCMS) is the "wave of the future" for batch production.

The application of industrial robots in activities relating to metal machining cells is receiving considerable attention. In the next few years, we can expect to see industrial robots being installed in many medium batch size manufacturing plants, servicing two or three computer numerically controlled (CNC) machines. There will be a strong emphasis on the use of inexpensive microprocessors that will coordinate the various pieces of hardware in such a cell. Machine tool builders are already committed to a strategy in which considerable programmability is embedded in the machine tool system itself. Systems are now commercially available that integrate all design and production stages between generating design drawings to generating the cutting instructions for a computer numerically controlled cutting tool. Stand alone robots are still crucial to the success of the total manufacturing operation. Consider the role of the robot in the cell in Figure 5. The part has to be moved from one machine to another. In addition to such manipulation within the cell, there is a potential need for robots to carry out preprocessing functions, such as cutting raw bar stock, and palletizing. There is also a need for supplementary functions, such as deburring, heat treating, surface plating, and assembly. From a human worker's viewpoint, there are many task within these activities, such as loading and unloading conveyors or pallets, that are monotonous and which suit the capability of a robot. Technical developments that enable robots to be more versatile will clearly lead to more widespread installation in the manufacturing industry. For example, the development of a "universal gripper" or the ability to identify and pick-up a part placed randomly on a moving conveyor or in a bin are important areas of current research.

In order to carry out a "closed loop machining operation" where the robot may also replace the routine metrology (measurement and inspection) operations in a manufacturing cell, tactile feedback is essential. While some dimensional measurement checks can be made on the machine tool itself with sensors placed in the tool changer, there will still be the need for measurement off line. Such measurements are normally done at present by human operators. In moving towards fully automated cells, the robot will also have to participate in this task via exact placement of parts in measuring stations. The rapidity with which robots that can "see" and "touch" are developed and accepted is of particular interest, since these capabilities appear to be vital for applications of robots to assembly and inspection.

The next step in systems integration is for several machining cells to be linked together in a Flexible Computerized Manufacturing System (FCMS). Workpieces with a given range of variability can be automatically subjected to differing production processes as necessary, by means of very sophisticated control and transport systems. The development of mini and micro computers for control has made FCMS practical. Robots interact with numerically controlled machine tools and other equipment, controlling the sequence of operations. It is more integrated and more automated than a traditional "job shop" consisting of machines in isolation, operated by individual humans. A number of such system shave been reported in the literature, including the Ingersoll- Rand system in the U.S., the East German "Prisma 2" System and the Japanese system known as the Methodology for

Figure 5: Robot Serving a Cell

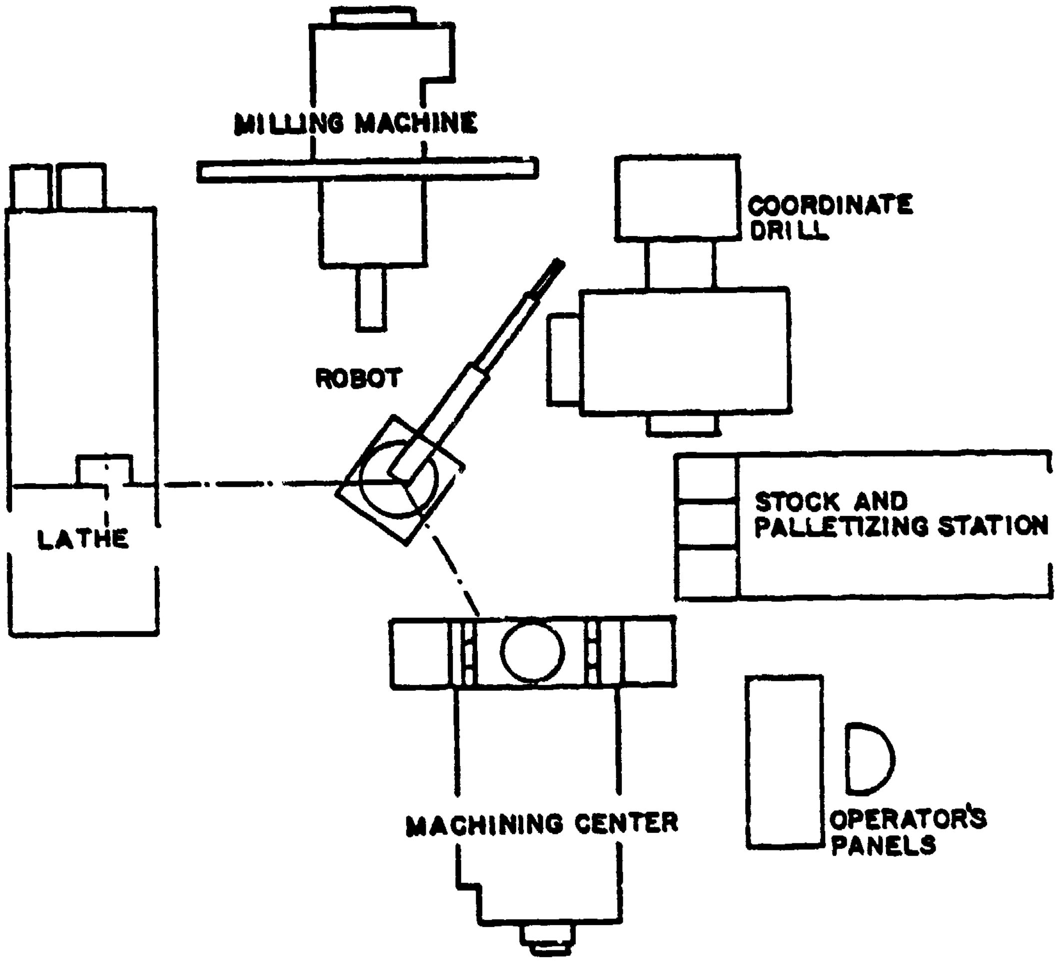
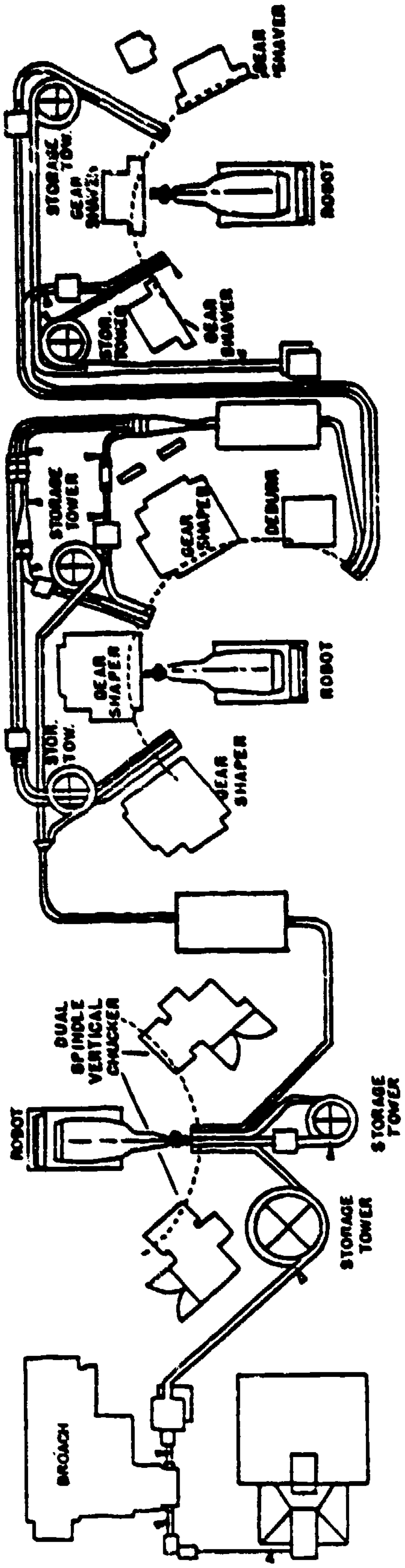


Figure 6: Flexible Computerized Manufacturing System



Unmanned Manufacturing (MUM). A relatively simple example is shown in Figure 6 representing a flexible three cell system for making planetary pinion gears at the Massey-Ferguson transmission and axle plant in Detroit. The manufacturer had originally planned for hard automation, but found the use of robots (instead of a customized transfer line) to be both less expensive and quicker to install. Several other systems are illustrated in (Lerner, 1981).

There is a fundamental reason why robot integrated FCMS may encroach in the traditional mass production area. It is because of growing consumer demand for *product diversification*, spurred by a variety of factors, including the introduction of new goods, shorter product life cycles, shifts in preferences, and a growing desire, and sometimes need, for more customized products. To achieve true diversity of products a more flexible manufacturing technology will be needed . Production runs will be shorter and changeovers more frequent. Most important, the need for extensive retooling to accommodate production redesign must be reduced or eliminated. Curiously enough, the way to increase flexibility in the mass production of consumer goods seems to be increased standardization of capital goods. Machines used to mass produce products , such as high speed transfer lines, are custom built for a single product, or for a small number of variants. As a result, mass-produced goods are not as cheap as they could be because they depend on specialized machines and equipment that are very costly by virtue of being 'custom' made in very small numbers. "Mass" production would be cheaper, clearly, *if the production equipment itself were also mass produced--or at least produced on a larger scale*. The virtue of programmable, general purpose robots is precisely that a standardized unit may be utilized in a large number of of different configurations, and situations, achieving specialization by software, rather than hardware.

Machines currently used for batch production, such as manually controlled, general purpose machine tools, or stand-alone NC machines, can be produced in much higher volumes then mass production machines since one type of machine can be used for a wide variety of purposes. However, the drawback to the current generation of general purpose, or so called flexible machinery, is that unit operating cost are high because of low output levels and high labor intensity.[6] The development of high performance, general purpose robots, and their integration into FCMS will eventually permit us to use mass produced machines to mass produce consumer products--a fairly revolutionary change.

An not-so-obvious implication of this trend is that an important existing inhibition on technological change in mass production industries may be relaxed.This is because the current generation of custom built mass production machinery is inherently inflexible. If the product is obsolete, the machine can only be scrapped,and replaced. If FCMS were successfully implemented throughout industry, product modifications, and product development would not be so costly. If computerized factories were so flexible that average unit cost of a thousand (or a million) copies of one product were the same as average unit cost of one copy of a thousand products, a new era of technological dynamism might follow.

[6] Many NC machines in use today still require one operator per machine per shift, the same as manually controlled machines

8 The Potential for Productivity Improvement

In the engineering sectors (SIC 33-38), average utilization of manually operated machine tools is remarkably low. Estimates range from 5% to 30 % in job shops and batch production, as compared to between 20 % and 40 % machine utilization rates attainable in typical mass production plants. Our estimates figures for the overall utilization rates of metalcutting, metalforming, and welding equipment are 12 %, 15 % and 22% respectively, assuming theoretical full utilization corresponds to 20 hours/day and seven days a week, to permit scheduled maintenance. Incomplete use of the second and third shift, and plant shutdowns account for some of the lost time. Scheduling inefficiencies, and set up time account for much of the remainder. Due to the complexities of scheduling, and mostly manual material handling systems, there is typically a large work-in-process inventory on the floor. Low machine utilization, and large quantities of work in process hold down capital productivity.

The introduction of computer aids in assembly line processes is expected to result in an improvement in material and labor productivity. Applications such as spray painting , cutting, and inspection are partly motivated by materials savings possibilities , and partly by quality control considerations If quality control is improved less material would fall out of the process. Less labor would go into rework, and less productive time and resources go into producing an excess percentage of output in anticipation of fallout.

The coming revolution in manufacturing technology, among other things, may greatly increase the efficiency of utilization of machine tools used in batch production. There is an important implication. Capital goods-- producer's durable goods including machine tools listed in Figure 7 -- are almost entirely batch produced. The use of robots and computer control mean that new capital goods will be much more productive than the old equipment it replaces. If the real cost of manufacturing producers durable equipment were reduced as a result of productivity improvements, the price of capital goods in relation to final products could be expected to decline fairly sharply over the next half century.[7] It is difficult to overstate the significance of this event. There would undoubtedly be a ripple effect on prices of manufactured goods throughout the economy, as outlined in Figure 8. We expect reductions in the real price of producer's durable equipment to reduce real unit capital cost in the sectors purchasing this equipment. We expect this effect to, in turn, reduce the real price of final output of mass produced consumer goods, as well as the real price of output of the nonmanufacturing sectors. Final demand might be stimulated to to some undetermined extent.[8] Lower real cost might incidentally have a very beneficial impact on the rate of inflation. If inflation is caused by "too much money-chasing to few goods", a sharp increment in productivity is perhaps the best way to break out of the vicious cycle. These second order effects, while less immediate, may have greater ultimate importance then the expected direct improvements in labor productivity in manufacturing.

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[7]The absolute price of capital may not decline, but we expect the price per unit of capability, or quality, to steadily decrease, as has been the case with computing equipment.

[8]It is possible that the real cost of manufactured goods could be reduced without necessarily increasing either real disposable incomes or demand. For example, if markets for many categories of standardized goods were nearly saturated, consumers would primarily buy to replace old, or worn out items, and not to increase their "stock " In this more wealthier society, people could choose to increase their leisure time, rather than increase their real buying power.

Table 5: Estimates of Productive Cutting Time in Metalworking Manufacturing

	LOW VOLUME	MID VOLUME	HIGH VOLUME
Productive Cutting Time	6%	8%	27%
Reasons for Lost Time			
Incomplete Use of 2nd and 3rd Shift	44%	40%	
Holidays and Vacations	34%		
Plant Shutdown		28%	27%
Work Standards Allowances and Miscellanecus Losses			16%
Load/Unload, Noncutting		4%	14%
Set-up,Gauging	12%	7%	
Tool Change		7%	7%
Equipment Failure		6%	7%
Inadequate Storage			7%
Idle Time	2%		
Cutting Conditions	2%		
Theoretical Capacity	100%	100%	100%

Source: *The Technology of Machine Tools, Volume 2: Machine Tool Systems Management and Utilization*, Lawrence Livermore Laboratory, 1980.

Table 6: Estimates of Average Machine Tool Utilization in the Metalworking Industries, 1977

SECTOR	METAL CUTTING TOOLS (%)	METAL FORMING TOOLS (%)	JOINING (Welding) TOOLS (%)
33	17.8	35.5	24.4
34	11.1	15.8	17.2
35	11.4	9.6	21.8
36	8.6	14.3	10.2
37	15.3	20.3	40.6
38	7.3	6.9	13.6

Assumptions.

Full utilization of a stand alone, manually controlled machine tool would be equivalent to 2 1/2 shifts, (20 hours/day) operation, seven days a week. This corresponds to 7280 manhours per year. Assume 2000 hours per worker per year. Thus one manually controlled tool requires 3.6 operatives per machine per day.

$$\text{Utilization} = \frac{\#\ \text{of Non NC machine operators} * 2000}{\#\ \text{of Non NC machines} * 7280}$$

Producers Durable Equipment

- **METAL-WORKING MACHINERY**
  - **Other Heavy Machinery**
    - Engines and Turbines
    - Farm machinery
    - Construction, mining, material handling equipmen
    - Other special industry machinery
  - **Other Machines, (non electrical)**
    - General industry machines
    - Office, accounting and computing equipment
    - Service industry machinery
  - **Electrical and Electronic Machinery**
    - Electric transmission, distribution equipment
    - Communications equipment
    - Other electric equipment
  - **Transportation Equipment**
    - Trucks, buses, trailers
    - Autos
    - Aircraft
    - Ships and boats
    - Railroad equipment
  - **Measuring and Controlling Equipment**
    - Instruments
  - **Fabricated Metal Products**
    - Heating equipment
    - Structual metal products
    - Forgings and stampings
  - **Furniture**

Figure 7: Categories of Producer's Durable Equipment

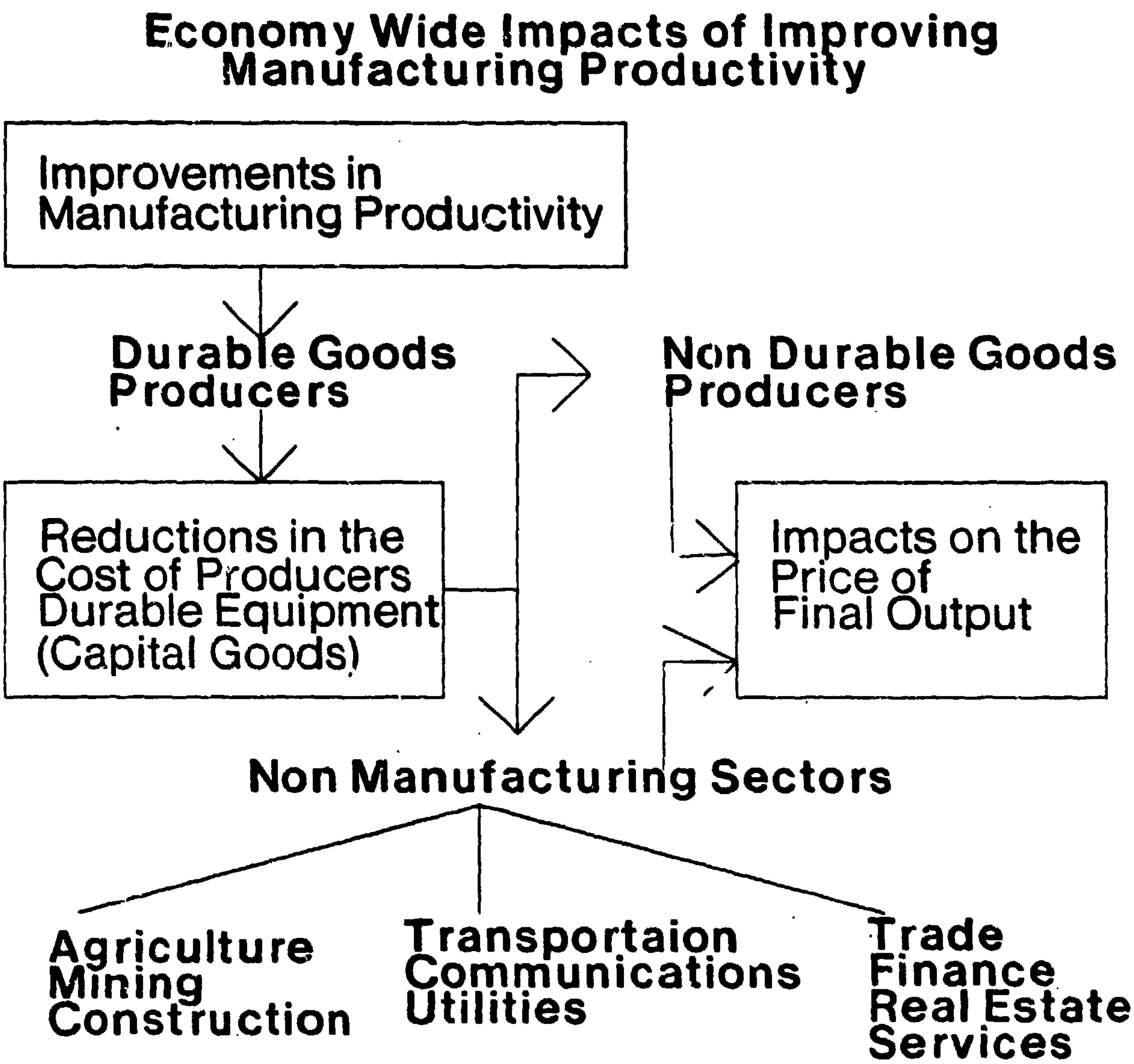

Figure 8: Economy Wioe Impacts of Improving Manufacturing Productivity

9 Societal Benefits Beyond Productivity

There are other major benefits to be gained from robotics, of scarcely less social significance in the long run. The first of these is to improve the quality of work-life. This is certainly a social benefit, even though it admittedly has a negative side. Throughout history, and continuing today, society has functioned, in part, by forcing very large numbers of people to perform dull, dirty, dangerous, degrading and/or demeaning (but necessary) tasks. Machines have gradually eliminated many of the worst of these tasks over the past two centuries. For example, in industrialized societies, humans no longer chop wood, plant, cultivate, or harvest crops by hand. Men no longer carry heavy loads on their backs. Women no longer have to weave cloth or wash cloths by hand. But traditional factories still use humans for many repetitive materials handling, machine loading/unloading, tool operating and parts assembly tasks.

These tasks, in general, make use of the high grade motor skills and natural eye-hand coordination of humans, without requiring either intelligence, judgment, or creativity. Being repetitive, they are inevitably boring. To the extend that such tasks involve manipulating heavy workpieces, high temperatures, the use of high speed tools or reactive chemicals, there is also inherently some degree of hazard. In the long run it can only be counted as a societal benefit if such tasks are taken over by machines, notwithstanding the fact that such tasks currently provide employment and wages for a number of unskilled and semi-skilled people who are unprepared by education or training to undertake more demanding kinds of work. Transitional issues and social cost are discussed later.

10 Motivations For Using Robots

As part of the recent Carnegie-Mellon University study on *The Impacts of Robotics on the Workforce and Workplace*, members of the Robot Institute of America were asked to rank the factors influencing their decision to install robots. Of the respondents, 19 were robot users, while 19 were considering adoption. The survey results are shown in Table 7.

Survey respondents *overwhelmingly* ranked efforts to reduce labor cost as their main motivation.[9] Users frequently pointed out that the return on investment (ROI) calculation would not be favorable unless there is a dramatic decrease in direct labor cost. Arguments for the benefits of expanding capabilities, such as improving product quality or increasing production flexibility were often considered "nebulous" by the financial analyst.

The question was raised as to whether experienced users *learn* how to quantify "indirect" benefits as they accumulate experience using robots. An executive at one firm speculated that inexperienced users only take direct labor cost into account because they do not know what other categories of cost will be affected. He said that his firm had learned how to quantify other indirect benefits such as improved product quality and reductions in indirect material requirements. Other experienced users did not report this kind of "learning".

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[9]Draper Laboratories, Cambridge.Mass., carried out a survey ranking motivations for using assembly robots in 1980. Their respondents also ranked direct labor cost as the primary motivation.

Table 7: Motivations for Using Robots

RANK	USERS	PROSPECTIVE USERS
1	Reduced Labor Cost	Reduced Labor Cost
2	Elimination of Dangerous Jobs	Improved Product Quality
3	Increased Output Rate	Elimination of Dangerous Jobs
4	Improved Product Quality	Increased Output Rate
5	Increased Product Flexibility	Increased Product Flexibility
6	Reduced Materials Waste	Reduced Materials Waste
7	Compliance With OSHA Regs	Compliance with OSHA Regs
8	Reduced Labor Turnover	Reduced Labor Turnover
9	Reduced Capital Cost	Reduced Capital Cost

Other factors mentioned:

- To give an image of innovativeness.
- To keep up with the Japanese.

SOURCE: CMU ROBOTICS SURVEY: APRIL, 1981

Broader strategic concerns such as long term competitiveness apparently are considered, yet they are seldomly mentioned as the most important motivations. Only one firm said outright that they had invested heavily in robotics to improve the quality and the competitive standing of their product. They were also the only firm to give strong emphasis to other "intangibles" such as improved production flexibility. Interesting enough, this spokesman was the only person among the many interviewed to say that applications were not evaluated primarily on the basis of ROI or payback period.

11 Uses of Future Robots

Future uses of robots are not limited to "operative" tasks in manufacturing. On the contrary, some of the most significant future uses of robots may be to provide feasible means of providing services or exploiting resources that cannot be provided or exploited at all at present. Handling dangerous radioactive wastes on a routine basis in a future disposal facility is one example.[10] The choice is between one kind of mechanization and another: human workers *cannot* be routinely exposed to these wastes. Mobile robots would offer a much greater degree of flexibility then teleoperators, or "hard" automation.

Exploration, mining, construction or other routine activities in hazardous environments are other examples. Such tasks are difficult, dangerous, and consequently inordinately expensive. Robots may

[10] A robot was designed by Hughes Air Craft in 1958 to handle radioactive materials at Atomic Energy Commission facilities in Albuquerque N.M. The U.S. Department of Energy is currently applications of robotics to nuclear reactor maintenance.

find use in coal or other mines, simply because mines are such unpleasant and dangerous work environments for humans. Robots could drastically alter the economics of commercial utilization of space, for example. In the long run, it is likely that *if* man succeeds in "industrializing" the moon, orbiting space colonies, asteroids or other planets, it will only be done with major assistance from robots. The Viking 2 Lander which touched down on the surface of Mars in September, 1976, is perhaps only the first of a line of "exploration" robots. Planned Mars surface rover missions will last 8-10 times longer than Viking and entail much greater complexity. The U.S. Navy and a number of other organizations are actively developing underwater robots or "unmanned submersibles" both for military and non-military purposes.

Finally, prosthetic robots and household robots exemplify service categories that are increasingly needed and difficult to obtain in any other way. Paraplegics, and especially quadriplegics, for instance, might be served full time by voice-activated robots capable of doing a variety of necessary tasks from feeding to page-turning. Such robots are being developed in Japan. In the U.S., the Veterans Administration has an ongoing program in Rehabilitative Robotics. The all purpose household "droid" robot is probably a rather visionary idea, at present, but robots could certainly be designed to perform some types of jobs, notably heavy cleaning. Joseph Engelberger, President of Unimation, has promised that he will soon have a robot (to be named Isaac,after Asimov) that will serve coffee in his office. Quasar Industries of Rutherford N.J. built and photographed a model "household" android in 1978, and announced their optimistic intentions for "mass production within two years." The project was somewhat of a hoax, but there is still unquestionable commercial interest in developing such a product if only because of the vast potential market. In fact, Nieman-Marcus Department Stores advertised a household robot (actually a remote controlled device) in their 1981 catalog. For every conceivable application of an industrial robot, there are at least ten applications for a household robot. It is impossible to believe that such a vast market will not be exploited at the earliest possible time.

It is vitally important to recognize the potential importance of some of these applications-- and some of their adverse consequences--in the picture as a whole. It is entirely conceivable , for instance,that a century hence historians looking back might say, in effect,"*the real significance of robotics development in the 1980's and 1990's is that they enabled mankind to expand his abode permanently beyond the earth's surface, and thereby escape the trap of limited resources associated with that constraint.*" All of future history could be very different, depending on whether space is successfully "colonized" in the next century or not. On the other hand, discounted present value criteria might tend to put more weight on proven short-run applications that pay off because of displaced labor then on very large but very remote benefits.It is to important to assess short-term benefits and costs, without unduly discounting long-term implications.

12 Short Term Transitional Problems

As part of a recent the Carnegie Mellon study, member firms of the Robot Institute of America (RIA) were also surveyed to determine the potential for robotization within various occupations. The RIA members were asked to estimate what percentage of jobs within a given occupational title could be done by a robot similar to those on the market today (Level I), and by the next generation of robots with rudimentary sensing capabilities (Level II). Based on the responses of 16 firms , several occupational titles were singled out as having a high potential for robotization, as shown in Tables 8 and 9. The responses to the survey were quite varied, reflecting the different requirements of similar jobs in various industries. The response from each firm depended on its products, the length of the typical production run, and on the experience of management with robots. Despite obvious limitations on the completeness of the survey, several occupational categories can still be targeted as prime candidates for replacement by Level I and Level II robots, even though there are some specific tasks within these occupations that will not be automated for many years to come.

12.1 Potential Displacement

Almost all of the present membership of the RIA--and 90 % of current robot users--fall within the metalworking sector. There are nearly three million workers employed in the nine occupations designated as the prime operative task for Level I and Level II robots in the metalworking industries (SIC 34-37) nationwide. Based on the average weighted response of the percent of jobs which robots could do, it appears that nearly half a million of these operatives could potentially be replaced by Level I robots. The figure roughly doubles to one million operatives if Level II robots with rudimentary sensing capabilities were available. Extrapolating the data for metalworking to similar task in other manufacturing sectors, it appears that Level I robots could eventually replace about one million operatives, and Level II robots could eventually replace three million out of a current total of 8 million operatives. We think the time frame for this displacement is *at least* twenty years, however.

By 2025, it is conceivable that more sophisticated robots will replace almost all operative jobs in manufacturing (about 8 % of todays workforce), as well as a number of routine non-manufacturing jobs. As we currently understand the situation, concerted efforts should be made by the private and public sector to redirect the future workforce in response to these changes. Even though several million operative jobs in the current manufacturing workforce are indeed vulnerable to robotization, the transition seems hardly catastrophic on a national scale, provided new job entrants are properly trained, and directed. In our view, the oncoming transition will probably be less dramatic than the impact of office automation over the same period. By 2025, most current operatives would have retired or left their jobs . The jobs would not disappear all at once, and robot manufacturing, programming, and maintenance itself will provide some new jobs, although we think most new jobs will *not* be in manufacturing, despite the rapid growth of the robotics industry itself. New "growth" sectors in the economy, including undersea and space exploration may also provide many new jobs. The important conclusion is that *young people seeking jobs in the near future will have to learn marketable skills other then welding, machining, and other operative tasks that are being robotized.*

Even though the adjustment problems seem manageable, the potential for social unrest in specific locations cannot be dismissed quite so lightly. Over half of all the unskilled and semi-skilled "operative" workers--the types of jobs which could be replaced by robots-- are concentrated in the four major metalworking sectors (SIC 34-37). Almost one half of all production workers in these four industries are geographically concentrated in the five Great Lakes States--Indiana, Illinois, Michigan,Ohio and Wisconsin-- plus New York and California. Within these same states, the metalworking sector also accounts for a large percentage of the total statewide employment in manufacturing. Adjustments in response to the rapid diffusion of robotics may be intensified in these areas. The impacts of not improving the productivity and competitive standing of these very same

Table 8: Prime Operative Tasks for Level I Robots

OCCUPATION	LEVEL I ROBOTS		LEVEL II ROBOTS	
	Range of Responses	Average Weighted Response	Range of Responses	Average Weighted Resp
Production Painter	30-100 %	44 %	50-100 %	66%
Welder/Flamecutter	10-60 %	27 %	10-90 %	49%
Machine Operator[11]		20 %		50 %
Machine Operators (NC)	10-90 %	20 %	30-90 %	49 %
Drill Press Operators	25-50 %	30 %	60-75 %	65 %
Grinding/Abrading Operators	10-20 %	18 %	20-100 %	50%
Lathe/Turning Operators	10-20 %	18 %	40-60 %	50 %
Milling/Planning Operators	10-20 %	18 %	40-60%	50 %
Machine Operators (Non NC)	10-30 %	15 %	5-60 %	30 %

Table 9: Prime Operative Tasks for Level II Robots

OCCUPATION	LEVEL 1 ROBOTS		LEVEL II ROBOTS	
	Range of Responses	Average Weighted Response	Range of Responses	Average Weighted Resp
Electroplaters	5-40 %	20 %	5-60 %	55 %
Heat Treaters	5-50 %	10 %	5-90%	46%
Packagers	1-40 %	16%	2-70 %	41 %
Inspector	5-25 %	13 %	5-60 %	35 %
Filers/Grinders/Buffers	5-35 %	20 %	5-75 %	35 %
Assemblers	3-20 %	10%	20-50 %	30 %

Based on 16 responses.

All Respondants did not give estimates for all occupations.

SOURCE: CMU ROBOTICS SURVEY: APRIL 1981

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[11] Machine tool operators includes the separate types of machinest listed below. These estimates are used as an average to approximate the percentage of all categories of machinest listed below which could be robotized.

industries will also be concentrated in the same few states. There may also be a disproportionate impact on racial minorities and women. Non whites account for only 11 percent of the national workforce, but comprise between 15 to 20 percent of of operatives and laborers. (See Figure 9.) Women employed in semi skilled and unskilled manufacturing jobs are less likely to be represented by labor organizations than their male counterparts. (See Figure 10.) DeFacto economic discrimination could accordingly increase.

It is often noted that technological displacement would be minimized if the rate of robot introduction were paced by the attrition rate. At this time, we cannot say whether or not this is a feasible strategy. An examination of industry attrition rates and of the age distribution of manufacturing operatives and laborers suggest this strategy is not feasible. According to Bureau of Labor Statistics data, only one to three percent of the workforce in metalworking [SIC 33-38] leave their place of work as a result of quits, discharges, permanent disability, death, retirement, and transfers to other companies. However, these figures may substantially underestimate the percentage of people transferring out of specific jobs , since they only include people who actually leave the establishment. Workers who transfer jobs within the same establishment would not be counted in currently published turnover rates.[12]

Contrary to the notion that many manufacturing workers are old and nearing retirement, the vast majority of the manufacturing workforce still has 20 or more years of active worklife ahead of them. As of 1980, between two thirds and three fourths of operatives and laborers were less then 45 years old, which means that barely a third of the workforce would be retired in the normal way by the year 2000. (See Table 11.) On the average, skilled workers are older, but they are not as likely to be replaced by robots in the near future.

13 Union Responses to Technological Change

Over one third of all wage and salary workers in manufacturing, and a significantly higher proportion of production workers--85 % of motor vehicle equipment operatives, 52% of laborers, 47 % of other durable goods operatives, and 41 % of nondurable goods operatives-- are represented by labor organizations. Over 90 percent of those represented actually belong to unions. (See Table 13.) Clearly, unions will be heavily involved in the mechanics of the transition to robotics. The major unions representing workers in the metalworking industries are listed in Table 12.

There are no reliable statistics which cross classify union membership by manufacturing industry, but it appears that almost all of the membership of the UAW, the IAM, the IUE, the UE, and the USW work in SIC 33-38, whereas most of the membership of the IBEW works outside of manufacturing.[14]

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[12] Based on unpublished data, the Bureau of Labor Statistics estimates that for every 100 welders in manufacturing this year, only 80 of them will stay in their jobs next year, although only a small fraction of the twenty who change jobs will leave their current place of work. Thus, actual turnover rates within a specific occupation may be much higher then the rate at which workers leave their current place of work.

[14] A Bureau of Labor Statistics spokesman says that the data on union membership by industry is so unreliable that they no longer publish it.

SEX/RACE DISTRIBUTION OF THE MANUFACTURING WORKFORCE, 1980

Percentage distributions:
M: male
F: female
W: white
NW: non white

Total Employed Persons: 97,270,000

	W	NW	Totals
M	51.7	5.8	57.5
F	37.1	5.4	42.5
Totals	88.8	11.2	100.0

SKILLED WORKERS

Machine Jobsetters: 658000

	W	NW	Totals
M	88.2	7.9	96.1
F	3.2	.7	3.9
Totals	91.4	8.6	100.0

Other Metalworking Craftworkers: 638,000

	W	NW	Totals
M	89.2	6.9	96.1
F	3.3	.6	3.9
Totals	92.5	7.5	100.0

SEMI SKILLED AND UNSKILLED WORKERS

Moter Vehicle Equipment Operatives: 431,000

	W	NW	Totals
M	65.7	14.6	80.3
F	15.1	4.6	19.7
Totals	80.8	19.2	100.0

Other Durable Goods Mfg. Operatives: 4,166,000

	W	NW	Totals
M	55.7	8.5	64.2
F	30.2	5.6	35.8
Totals	85.9	14.1	100.0

Non Durable Goods Mfg. Operatives; 3,290,000

	W	NW	Totals
M	35.0	6.6	41.6
F	47.3	11.1	58.4
Totals	82.3	17.7	100.0

Manufacturing Laborers: 961,000

	W	NW	Totals
M	68.0	16.3	84.3
F	13.0	2.7	15.7
Totals	81.0	19.0	100.0

SOURCE: CURRENT POPULATION SURVEY, BUREAU OF LABOR STATISTICS

Figure 9: Sex/Race Distribution of the Manufacturing Workforce, 1980

Sex/Race Distribution of Manufacturing Workers Represented By Labor Organizations, May 1980

Percentage distributions:
M: male
F: female
W: white
NW: non white
(*): Base less than 75,000

Total Wage and Salery Workers: 22,493,000

	W	NW	Totals
M	30.3	36.6	31.0
F	17.5	27.4	18.9
Totals	24.9	32.1	25.7

Totals = percent of occupation group represented by labor organization

SKILLED WORKERS

Machinest and Jobsetters: 397,000

	W	NW	Totals
M	58.0	(*)	58.2
F	(*)	(*)	(*)
Totals	56.7	(*)	56.6

Other Metalworking Craftworkers: 423,000

	W	NW	Totals
M	63.3	(*)	63.7
F	(*)	(*)	(*)
Totals	62.8	(*)	63.1

SEMI SKILLED AND UNSKILLED WORKERS

Motor Vehicle Equipment Operatives: 315,000

	W	NW	Totals
M	85.5	(*)	87.1
F	(*)	(*)	(*)
Totals	85.3	87.9	85.8

Other Durable Goods Mfg. Operatives: 1,917,000

	W	NW	Totals
M	53.4	55.2	53.6
F	33.8	43.0	35.2
Totals	46.1	50.5	46.8

Non Durable Goods Mfg. Operatives: 1,320,000

	W	NW	Totals
M	51.2	52.5	51.4
F	33.5	32.1	33.2
Totals	41.0	40.1	40.8

Manufacturing Laborers: 436,000

	W	NW	Totals
M	55.3	48.9	54.1
F	40.5	(*)	41.7
Totals	52.8	49.2	52.2

SOURCE: Earnings and Characteristics of Organized Workers, May, 1980, BLS, Sept. 1981

Figure 10: Sex/Race Distribution of Manufacturing Operatives and Laborers Represented by Labor Organizations

Table 10: Annual Average Turnover Rates in Manufacturing, 1980

	Total Separation[13] rate for wage salary workers (per 100 employees)	Layoff rate	Total Separation - Layoff = Attrition
Manufacturing, total	4.0	1.7	2.3
Durable goods, total	3.8	1.8	2.0
Lumber	6.0	2.7	3.3
Furniture	4.5	1.5	3.0
Stone,Clay, and Glass	4.3	2.2	2.1
Primary metals	3.8	2.5	1.3
Fabricated metals	4.3	2.1	2.2
Machinery,exp. electrical	2.8	1.1	1.7
Electrical machinery	3.2	1.1	2.1
Transportation equipment	4.2	2.5	1.7
Motor Vehicles and equip.	6.0	4.5	1.5
Aircraft and parts	1.6	.3	1.3
Instruments	2.4	.5	1.9
Miscellaneous	5.3	2.4	3.1
Non Durable Goods	4.3	1.6	2.8
Food	6.2	2.8	3.6
Tobacco	3.6	2.0	1.6
Textile Mill	4.1	1.0	3.1
Apparel	5.7	2.1	3.6
Paper	2.9	1.2	1.7
Printing	3.2	.8	2.6
Chemicals	1.8	.5	1.3
Petroleum Products	2.1	.8	1.3
Rubber/Plastic	5.1	2.2	2.9
Leather	6.8	2.5	4.3

Employment and Earnings, March 1981. Bureau of Labor Statistics. Series D-2. Establishment Data, Labor Turnover, Annual Averages.

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[13] *Total separations* are terminations of employment initiated by either employer or employee. (Rates per 100 employees.)*Layoffs* are suspensions without pay for more than 7 consecutive initiated by employer.(*Total separations - Layoffs*) includes quits, discharges,permenant disabilities, retirements ,transfers to other establishments, and entrances into the Armed Forces. Workers who change jobs, but do not leave their place of work are not included in these figures.

Table 11: Age Distribution of the Manufacturing Workforce, 1980

Occupation	Number Employed (000'S)	16-19	20-24	25-34	35-44	45-54	55-59	60-64	65+	% 45 or younger
		Percentage Distribution by Age Group								
TOTAL EMPLOYED	97,290	7.8	14.0	27.0	19.8	16.7	7.2	4.5	3.0	69.0
Machine Jobsetters	658	3.3	15.2	27.8	19.6	17.6	9.4	5.8	1.3	66.0
Other Metalworking Craft Workers	638	2.0	9.6	28.8	20.8	20.0	11.0	6.7	1.1	61.0
Motor Vehicle Equipment Operatives	431	2.1	11.3	30.6	25.9	20.1	5.8	3.9	.2	70.0
Other Durable Goods Operatives	4,166	5.5	17.5	27.9	19.5	16.6	7.4	4.5	1.1	70.0
Non Durable Goods Operatives	3,290	6.5	16.0	26.3	19.3	18.5	7.5	4.5	1.4	68.0
Manufacturing Laborers	961	9.7	20.3	28.2	16.5	14.1	5.9	3.8	1.4	75.0

Source: Current Population Survey, Bureau of Labor Statistics. Annual Averages for 1980.

Table 12: Major Unions Representing Workers in the Metalworking Industries

UNION	MEMBERSHIP, 1978 (000's)	MEMBERSHIP 1980 (000's)
United Automobile, Aerospace and Agricultural Implement Workers of America (UAW)	1,499	1,357
United Steelworkers of America (USW)	1,286	1,238
International Brotherhood of Electrical Workers (IBEW)	1,012	1,041
International Association of Machinest and Aerospace Workers (IAM)	724	754
International Union of Electrical, Radio and Machine Workers (IUE)	255	233
United Electrical, Radio and Machine Workers of America (UE)	166	162

Source for membership figures:
1978:Directory of National Unions and Employee Associations, 1979. Bureau of Labor Statistics, Sept. 1980. Bulletin 2079
1980: Principal U.S. Labor Organizations, 1980. Bureau of Labor Statistics.

Collective bargaining contracts are the formal mechanism that unions use to affect company policies . Union contracts are marked by their large number, and by their diversity of provisions and their sphere of influence. A comprehensive review of union contracts is beyond our scope. However, as part of the project on *The Impacts of Robotics on the Workforce and Workplace*, we reviewed representative contracts from the UAW, the IAM, the IBEW, and the IUE, and identified clauses relating to the introduction of new technology. The union contracts include clauses relating to job security, job integrity in the workplace, and benefits to the workers in the event of a lay-off. Job security attempts to provide workers with guaranteed of continued employment at agreed upon wage and benefit levels while job integrity deals with the maintenance of the bargaining unit in the face of changes in the production process. Such clauses encompass concerns relevant to the actual working conditions of the firm. In the event that job security is not attainable, the unions attempt to ease the situation of the individual worker in the period after displacement.

Three of the four union contracts studied had provisions which set up joint union-management committees to discuss the phasing in of new technology. These committees receive advance notice of impending technological changes, and when necessary, negotiate possible policies to mitigate the negative effects with the collective bargaining unit. These policies included advance notification to workers, agreements to minimize displacement, and provisions for retraining. Some of the specific clauses found in the contracts studied are listed below. A more detailed breakdown of clauses by by union is shown in Table 14.

Table 13: Wage and salary Workers Represented by Labor Organizations, May 1980

	Percentage of employed wage and salary workers represented by labor organizations	Number of employed wage and salary workers represented by labor organizations (000's)	Number of represented workers in unions (000's)
ALL OCCUPATIONS/INDUSTRIES	25.7	22,493	20,095
MANUFACTURING OCCUPATIONS			
Machinest and job setters	56.9	397	381
Other metalworking craft workers	63.1	423	411
Motor vehicle equipment operatives	85.8	315	312
Other durable goods operatives	46.8	1,917	1,802
Non durable goods operatives	40.8	1,320	1,244
Manufacturing laborers	52.2	436	420
MANUFACTURING INDUSTRIES			
Manufacturing, total	34.8	7,309	6,771
Durable goods, total	37.6	4,720	4,366
Ordnance	20.9	86	74
Lumber	20.9	113	103
Furniture	28.6	132	124
Stone,Clay, and Glass	49.4	305	292
Primary metals	60.5	712	686
Fabricated metals	39.0	530	491
Machinery,exp. electrical	30.6	851	798
Electrical machinery	30.1	672	599
Transportation equipment	55.9	1,135	1,038
Automobiles	63.1	600	582
Aircraft	50.4	341	286
Other trans. equip	48.1	194	170
Instruments	14.5	90	79
Miscellenous	18.8	93	82
Non Durable Goods	30.7	2,589	2,405

Earnings and Other Characteristics of Organized Workers, May 1980
U.S. Department of Labor. Bureau of Labor Statistics. September, 1981.
Bulletin 2105

- Sharing of Increased Productivity Benefits
- Paid Personal Holidays
- Supplemental Unemployment Benefits
- Transitional Allowances
- Advance notice of Technological Change
- Severance Pay
- Retraining Provisions
- Integrity of the bargaining Unit

These provisions have evolved over the years as part of an arrangement between the unions and the firms to soften, or offset the impacts of displacement resulting from technological changes. Technological change, in the view of the unions, results not only from the introduction of new labor saving machinery, but also from design changes in the product, changes in engineering strategies, and other types of modifications that "speed up the line", or reduce unit labor requirements. Another intent of these provisions is to share some of the benefits of improved profitability with the workforce.

Provisions calling for the *sharing of productivity benefits* are based on the assumption that technological improvements which increase productivity should in turn increase corporate profits. By sharing the increased profits with the union, the company might improve the acceptance of new technology. In the contracts studied, the UAW's Wage Improvement Factor was the only example of a clause explicitly calling an annual percentage "productivity increase" exclusive of cost of living increases. A UAW spokesman commented that this type of clause is only negotiated if the plant is in a position to pay for it, and that where it has been negotiated, productivity has improved by more then the wage improvement factor.

Paid Personal Holidays (PPH) are intended to spread fewer available jobs among a greater number of employees by giving workers additional days off with pay in addition to holidays. The UAW has negotiated twenty six Paid Personal Holidays over a three year period for each member working for an automobile manufacturer.(About 50 percent of the UAW membership.) The intent is to reduce the number of workers laid off by reducing the number of days worked per employee. Other unions have implemented similar plans by increasing the standard vacation time. A UAW spokesman commented that PPH's, like the Wage Improvement Factor, are negotiated when productivity is increasing within the plant, and unit labor requirements are decreasing. The spokesman also emphasized that PPH's were only one part of a total package for offsetting displacement accompanying productivity improvements. The additional paid holidays can also be viewed as another means of sharing the benefits of increased productivity.

Supplemental Unemployment Benefits are used in addition to unemployment compensation to aid workers through lay off periods. Nationally, the UAW is the principal advocate of this program.

Table 14: Characteristics of Union Clauses Relating to the Introduction of New Technology

Characteristics of Clauses Relevant to the Introduction of New Technology

	UAW	IAM	IUE	IBEW
Retraining provisions, cost burden on employer	new position retraining determined by a committee of management and union representatives	company responsible for establishing retraining programs at its own expense and during regular work hours	company will make available specialized training for qualified workers displaced by technology	
Paid personal holiday	workers become eligible for PPH after one year of seniority and a set number of pay periods per year			
Relocation allowances	amount of allowance ranges from $500 to $1760 depending on workers marital status and transfer distance. Seniority and other benefits unaffected	company provides moving arrangements and pays transfer costs: transferred employees carry all rights except seniority to new plant: seniority at new plant starts on first day		
Advance notice	advance notice provided through a National Committee on Technological Progress comprised of union and management representatives	a joint union-management Committee for Technological Change will study effects of technological change on workers	a joint union-management committee will discuss impact of technological change on workers	company retains sole right to manage its business including right to introduce technological improvements
Sharing of increased productivity benefits (wage improvement factor)	exclusive of cost-of-living, management profits from new technology are shared with the UAW			
Supplemental unemployment benefits	set to aid laid off auto workers			employees receive a retirement service, if eligible, or a termination allowance
Severance pay				employees eligible after five years of service: these employees will retain all rights and privileges

Source: Compiled from Collective Bargaining Agreement Between General Motors Corporation and the UAW 1979; Columbia Lighting Co. and IBEW Local 73, 1979-1982; General Motors and IUE 1979; and the IAM Model Contract.

Transitional Allowances are provided to workers when the firm transfers employees from plant-to-plant. These allowances ranged from $500 to $1760 per employee in the four contracts we reviewed. In some cases, benefits will also follow transferred employees. Seniority does not transfer for the IAM.

Advance Notice of technological change is required in all four of the contracts reviewed. The extent of union input and involvement varied among the four unions. The UAW and the IAM have committees consisting of both union and management representation which would study and discuss each change in technology, whereas, the IBEW contract indicates that management retains the sole right of controlling the introduction of new technology.

Severance Pay is used to provide for workers who are permanently laid-off. It effectively pays workers to leave their jobs. Severance pay is often used in cases of special retirement, where workers are paid lump sums to leave the job, in addition to receiving a percentage of their original pension benefits. This plan provides the firm with a quick, but costly means of reducing the size of the workforce.

Three of the four unions studied have negotiated *retraining* provisions as the responsibility of the employer. The IUE has stated that it will make available specialized training for qualified workers displaced by new technology. The UAW has training and retraining programs operating on an ongoing basis.

The Integrity of the Bargaining Unit has also been negotiated in recent collective bargaining agreements. The UAW has several agreements stating that all jobs previously in the bargaining unit will stay in the unit. In other words, if an operator in a bargaining unit is replaced by a robot, then the robot's operator will also be in the unit.

14 Broader Economy Wide Issues

The analysis of potential displacement, described in the previous section, would provide useful information to human resource planners , but does not address the critical issue of how robotics will effect employment throughout the entire economy. We view the long term economic growth issue and the *economy wide* employment impact as the highest level constraint and information input into human resource planning. Even though robot manufacturing, programming, and maintenance itself will provide some new jobs, it appears that most new jobs will not be in manufacturing. Yet, we have no idea of how many of these displaced workers and new workers can be expected to be absorbed in other sectors. This issue must be addressed if we are to go beyond identifying vulnerable workers, and actually prepare them --as well as the entering workforce-- for the likely changes to come

We are in the process of exploring the relationships between the increased use of robotics and the potential for economic growth throughout the whole economy. Even if robot users --primarily durable goods producers --were to reduce their production costs in real terms, we do not know if the rest of the economy would experience high enough levels of economic growth to offset the predictable losses in manufacturing employment. The link between the main tangible benefit of robotics--

reduction in the cost of capital-- and the potential for economic growth throughout the whole economy is still unexplored. *The bottom line is whether we can hope to realize a net social benefit-- including an net increase in employment-- by accelerating the use of robotics in manufacturing.* It is understood that there may be additional benefits in other areas, such as space or undersea exploration. But it is important to know if the required levels of economic growth can be achieved in the economy as it is now structured, without having to depend on the opening up of new frontiers. If these growth and employment levels can not be achieved as a result of cost saving process improvements in manufacturing, resources may have to be reallocated to encourage the creating of new products, services, and possibly, the development of new frontiers. This would require a reevaluation of the current policy emphasis of stimulating economic growth by improving the efficiency of creating "conventional" goods and services.

As mentioned earlier, we expect the primary quantifiable economic effect of robotics and programmable automation to be a reduction in the real cost of manufacturing products made in small to medium 'batches'--particularly, producers durable equipment. This rasies several important questions. The first relates to how much of an impact robotics will have on the economics of batch production. The second relates to the extent to which improvements in productivity in the capital goods sector may impact the price of output in other sectors that purchase these capital goods. These linkages are shown in Figure 11.

ECONOMY WIDE IMPACTS OF ROBOTICS

Tracing the links between

Improvements in manufacturing productivity → reductions in the real cost of producers durable equipment → Impacts on the price of final output → Impacts on the demand for final output ↓ Impacts on Employment Outside of Manufacturing

Figure 11: Analyzing Economy Wide Employment Issues

A first step toward estimating the potential for productivity improvement in batch manufacturing is to estimate the potential for reducing inventory carrying cost and set-up cost, and other benefits associated with increased machine utilization However, the replacement of new robotic systems for conventional technology may fundamentally alter the user's fixed and variable cost structure, as well as create new technological and economic possibilities. Thus, the analysis is not so clear cut.

To trace the impacts of reductions in the real cost of capital goods on the price of all other goods, we can, in principle, identify the durable goods content of all other goods and services. For example, even a piece of fruit has a large durable goods content since it requires planting, spraying, harvesting, processing, packing, and shipping. Input-output structures, and capital flows matrices identify these relationships, and can be used to estimate the extent to which the use of robotics might impact the prices of the current bundle of goods in the economy. Unfortunately, there is not clear cut way to estimate the extent to which a more productive manufacturing sector would spawn new economic goods and services.

The limitations of trying to estimate the indirect impacts robotics and programmable automation may have on economywide employment and economic growth should be acknowledged. While this may be the curcial issue, it is also the hardest to analyze with any degree of precision. Employment projections issued by the Office of Economic Growth in the Department of Labor, and by other research institutions (Chase, DRI, Wharton,etc.) estimate the growth of the labor force, based on estimates of final aggregate demand. There are several problems with this procedure, primarily imposed by the current limitations of economic science itself. One problem is that existing input - output tables used in the analysis reflect historical--but not necessarily future-- technological relationships. These models do not anticipate the basic structural changes we foresee in manufacturing, which might alter input- output relationships in important ways. Another comment is that multiplier effects of productivity improvement are not explicitly dealt with . These models do not incorporate the feedback effects these changes might induce in other sectors of the economy. Another important restriction is the lack of knowledge about price and demand relationships, particularly about how changes in price might trigger substitution effects. While the BLS, and other forecasters have already published projections of economy wide employment for the end of this decade, it must be pointed out that these models, in their current form, are not intended to assess, and may not even be capable of assessing the impacts of robotics and programmable automation on employment,either in manufacturing, or throughout the whole economy.

15 The Problem of Human Capital

Most of the published literature on robots describes physical capabilities and particular applications, or deals with the narrowly defined economics of robot use. based primarily on the difference between amortized robot cost and the "all-included" cost of hourly labor. Discussions of human factors, if any, tend to be sweeping statements about the importance of gaining the acceptance of workers and top management support, limiting human factors concerns to bypassing, or eliminating po[illegible]tial [illegible]'s of resistance to robotics. There has been little serious discussion to date of how to cope with the hard reality of developing needed new work skills on the one hand and how to deal with people who have obsolescent skills, on the other.

Robot users have been reluctant to discuss plans for robot use in the future, even though many manufacturers are testing a[illegible]ations. They argue that such information must be kept confidential for competitive reasons. O[illegible] result of private industry's uncommunicative attitude about future plans is that very little is being done to warn or prepare those workers whose jobs may be eliminated, or substantially modified as a direct, or indirect result of introducing robots. In the absence of solid facts, or even informed speculations as to what types of adjustments might occur, and their time phasing and magnitude, unions, media reporters, and government officials have started to suspect the worst, and ask: How many people will lose their jobs as this new wave of automation sweeps through industry ? Private industry undoubtedly has an interest in the public perception of the impacts of robots on the labor force. If the phasing in of robots is handled ineptly and insensitively,(or if people even think this is the case), unions, and other factions of society might conceivably find enough common interest-- based on a fear of technology-- to organize a "Neo Luddite" attack on robots and other forms of automation. Short of this extreme scenario, widespread social dissension could occur, fed by distrust of business and dissatisfaction with the record of a capitalist society in dealing with festering social problems.

To develop the necessary human capital at both the institutional and individual level, and to smooth the short term transitory impacts on the labor force, all the major actors must commit themselves to a cooperative effort to prepare and assist the workers most likely to be affected by the changes to come. To effectively prevent social trauma due to rapid introduction of robotics, without impeding technological progress itself requires:

- Identification of vulnerable categories of workers well in advance of actual job elimination.
- Long Range Planning by industry and government for future employment needs and new job skill requirements.
- The provision of **effective** education and training facilities to upgrade workers from skill categories that are, or will be in surplus supply to skill categories that are scarce.
- The provision of **effective** facilities to locate suitable jobs and place workers in them, with relocation assistance if necessary.

It is in industry's interest to assume a more active role in planning future employment needs. It must ensure that the workforce gets an accurate preview of the requirements of tomorrow's workplace, and that the appropriate skills are sought and taught.

Colleges and universities in the United States do a reasonably good job at educating science and traditional engineering students. But many of our existing educational institutions do not have the capability, or even the inclination to involve themselves in training unskilled or semi-skilled people for operational functions in industry. Experience with publically sponsored training programs suggest that, while they are reasonably capable of retraining skilled workers to do new jobs, they have seldomly been successful at training the "hard core" unemployed to be productive. *The educational establishment must face up to this problem , since some of the factory jobs which have historically employed the least skilled workers--such as material handlers and machine loaders/unloaders-- will eventually be replaced by robots. The same is true of many semi-skilled jobs such as welding.*

The educational establishment also needs to face up to several important deficiencies. There is too much emphasis on education for white collar jobs as opposed to training people to work with (i.e. supervise, maintain, and repair) machines. It appears that blue collar and skilled workers do not have a favorable image in our society, despite the fact that many of these jobs require more schooling, and pay comparable wages. Trade school is often viewed as an alternative for students who flunk out of the academic track, or for delinquents. The more capable students are steering away from factory work.

The Unions and management need ways of interacting cooperatively--rather than as adversaries--for dealing with issues of displacement and of changes in the workplace.

It would seem that if industry continues its uncommunicative policy , the unions will continue to emphasize setting precedents in order to ensure their survival in an uncertain environment. This type of "gaming " obstructs the type of planning that both unions and management need to do in cooperation with each other to solve real problems and achieve mutual benefits. It is not reasonable to expect firms to be more open with the unions if such disclosures would would constrain them in what type of technology they could develop, or how they could use it. Neither is it reasonable to expect unions to be more cooperative with management, and more flexible in their bargaining positions, if such an attitude would threaten the security of their workers and the long term viability of the unions themselves. The only way for both sides to break out of this bind is for government to change the conditions under which unions and industry talk to each other. In this context, the US may have much to learn from Japan, Germany, and other industrial countries.

Another of the government's key roles should be to provide incentives which would induce industry to take positive action on upgrading its human resources now. For example, the government could give tax incentives to partially reimburse industry for education and training investments in their employees. It could provide more favorable tax treatment for individuals who undertake formal retraining programs in mid-career. And, of course, it could provide inducements (financial and other) to educational institutions to induce them to redirect their efforts into new areas.

Education and training are established functions of all levels of government. It is vital that publically funded education/training programs reflect the emerging-- rather than the obsolete -- needs of industry and society . Vocational education enrollments and completions in six metalworking occupational categories are shown in Table 15. These six categories account for just over three percent of all vocational education enrollments for FY 1978.[15] Several popular occupational categories for publically funded training programs are precisely those which have been identified as prime candidates for robots. It appears that public education institutions in the US have not yet recognized the future employment skill needs of society. Training programs funded directly by government have an incentive to get people through a program quickly, and document their "success", even if they are providing people with obsolescent skills.

The future outlook for employment within most factory occupations cannot be extrapolated from historical data. The basic technological relationships governing the mix of labor and capital required to satisfy a given level of output are changing in very fundamental ways. Yet , government publications are still projecting employment requirements for many of the factory occupations without any explicit acknowledgement the impact of emerging production technologies--including robotics.

Long range planning of employment requirements and identification of vulnerable job categories

[15] Machinest and machine operatives, and welders account for slightly less then four percent of the employed workforce.

Table 15: Enrollments and Completions in Public Vocational Education in Selected Metalworking Occupations: National Totals: FY 1978

OCCUPATIONS	ENROLLMENTS	COMPLETIONS
Machine Shop Occupations	117,069	32,588
Machine tool Operations	14,232	3,437
Sheet Metal	45,694	6,571
Welding/Cutting	205,486	51,722
Tool/Die Making	8,475	2,369
Other Metal Working Occupations	58,709	17,548
Totals	449,665	114,285

Source:
Occupational Projections and Training Data, 1980 edition
U.S. Department of Labor
Bureau of Labor Statistics, Bulletin 2052

cannot be carried out by government agencies, such as the Bureau of Labor Statistics, without inputs from industry. Neither industry nor society at large can afford the consequences of having too many people steered into obsolescent occupations while there are too few people with badly needed skills.

1 A Chronology of Significant Devices and Events in the History of Robotics

This is a preliminary, as well as a partial chronology of significant developments in robotics technology. The list is compiled from the source material described in (Ayres, Lynn and Miller, 1981), and from (NSF81), (Reichardt, 1978), and (McCorduck, 79).

KEY

P # = patent number
A: Date patent applied for
I: Date patent issued

1720's	First programmable looms controlled by punch cards developed in France.
1801	Mass Production of card programmable Jacquard loom in France.
1822	Babbage completes first working model of the Difference Engine for automatic computation of tables in England.
1830's	Development of the Automat, a cam programmable lathe, by Spencer in the US.
1892	Motorized crane with a gripper for removing ingots from a furnace patented by Babbitt in the US. P # 484,870. I:1892.
1921	Carl Capok's Play, R.U.R. opens in London. The word "robot" is popularized.
1938	Position Controlling Apparatus -a programmable paint spraying machine developed by Pollard in the US. P # 2,286,571 A:1938 I:1942
1939	Means for Moving Spary Guns or Other Devices Through Predetermined Paths- another programmable spray painting machine developed by Roselund, working for De Vilbiss, in the US. P # 2,344,108. A:1939 I:1944.
1944	The Mark I computer, an electromechanical automatic sequence control calculator, is built by IBM and Harvard at Harvard. Principle Developer: Howard Aiken.
1946	The ENIAC, the first large electronic computer, is built by the Army and the University of Pennsylvania, at Penn. Principle Developers: Eckert and Mauchly.
1946	Magnetic Process Control- a general purpose analogue storage device- developed by Devol in the US. P # 2,590,091. A:1946 I:1952
1947	Servomechanisms Lab opened at MIT.
1948	Norbert Weiner publishes first edition of "Cybernetics". Concepts of communication and control (feedback) are popularized.
1951	First version of the ENIAC- the Univac- is delivered to the Census Bureau.
1951	System for controlling Automatic Machine Tools- a general purpose digital program storage device-developed by Lippel in the US. P # 2,927,258. A:1951 I:1960
1951	Electrical Manipulation Device- a remote controlled teleoperator with an articulated arm- is developed by Goertz, working for the Atomic Energy Commision. P # 2,695,715. A: 1951 I:1954
1952	IBM's first commercial computer-the 701- is built.
1952	First numerically controlled machine tool developed by MIT Servomechanism Lab and the Air Force at MIT.
1954	Remote Station Manipulator-a remote controlled teleoperator with an articulated arm -is developed by Bergsland, working for General Mills.

	P # 2,861,701. A:1954 I:1958
1954	Programmed Article Transfer Device-first robot with point to point control and an electronic playback memory-developed by Devol in the US. P # 2,988,237. A:1954 I:1961
1956	Dartmouth Conference on the future of Artificial Intelligence.
1957	Automatic Handling Mechanism- cam programmable, "pick and place" robot- developed by Brown,-working for the Planet Corp in the US. P # 3,051,328 A:1957 I:1962
1957	First General Problem Solver (GPS)-a computer program which codified a number of general purpose problem solving techniques- developed by Newell, Simon, and Shaw.
1959	First commercially available robot sold by Planet Corp.
1960(?)	Devol's patents acquired by Consolidated Deisel (Condec) Corp. The Unimate robot is developed from Devol's original device.
1960	Machine For Performing Work- programmable robot- developed by Johnson, working for American Machine and Foundry (AMF). P # 3,212,649 A:1960 I:1965
1960	Mobile two armed manipulator remotely controlled by an operator built by Huges Aircraft to work in radioactive environments.
1962	Mechansim for Remote Manipulation of Industrial Objects- programmable robot- developed by Kaye, working for AMF. P # 3,173,555 A:1962 I:1965
1962	Devol develops a "teachable" machanical program controller providing a quick and accurate way of making robot programs. P # 3,279,624 A:1962 I:1966
1963	Coordinated Conveyor and Programmed Apparatus-coordination of a robot and a conveyor line - developed by Devol. P # 3,306,442. A:1963 I:1966
1963	Devol develops a micromanipulator for his robot. P # 3,233,749 A:1963 I:1966
1963	Devol develops force sensing for his earlier device. P # 3,251,483 A:1963 I:1966
1964	Multi-Program Apparatus -a control mechanism which can branch to one of several recorded programs, based on external stimuli- developed by Devol. P # 3,306,442 A:1964 I:1967
1964	Devol develops continous path control for robots, and a mechansim for swithing between point-to-point and continous path control. P # 3,306,471 A:1964 I:1967.
1964	The UMAC control- the first commercially available general purpose controller- released by Remington Rand.
mid 1960's	Robotic Research Labs established at MIT, Stanford Research Institute, Stanford, and The University of Edinbourgh.
1966	Direct Numerical Control of Machine Tools with a "behind the tape reader" interface developed by Cincinatti Milacron.
1968	First version of the SHAKEY-an "intelligent" mobile robot- built at Stanford Research Institute.
1968	Robot controlled by a general purpose PDP-6 computer built by Max Ernst at MIT.
1968	Scheinman builds his first small hydraulically powered arm at Stanford.
1970	Scheinman builds first small electrically powered arm at MIT.
1971	Second version of SHAKEY robot build at Stanford Research Institute.

1971	"Structured Light" vision system developed by Agin and Binford at Stanford, by Will at IBM, and by Shirai.
1971	WAVE-the first robot programming language to automatically plan smooth trajectories, and which could use rudimentary force and touch sensing to control a manipulator-developed at Stanford.
1972	Force Vector Assembly Concept- using forces as inputs to a servo controller to guide parts assembly- developed at Charles Stark Draper Labs, in Cambridge, Mass.
1973	Method and Apparatus for Controlling Automation Along a Predetermined Path- the control system for the T3, the first commercially available computer controlled robot- developed by Hohn, working for Cincinatti Milacron. T3 is controlled by a minicomputer. P # 3,909,600 A:1973 I:1975
1973	First computer integrated robot assembly station developed at Stanford. Ten component automobile water pump is assembled.
1974	First version of AL- a robot programming language for real time control of concurrent multiple devices with sensory/motor control- developed at Stanford.
1974	Three legged walking machine built at University of Wisconson.
1974	Scheinman founds Vicarm to develop his robot arm. First Vicarm robot controlled by a minicomputer in same year.
1974	Olivetti builds robot controlled by minicomputer.
1975	The LSI-11 microprocessor is commercialized by Digital Equipment Corp.
1976	Viking I robot rover, built by NASA, lands on Mars.
1976	First robot controlled by a microprocessor is built by Vicarm. The first Scheinman arm controlled by a LSI-11 is shipped to the Navy Research Lab.
1976	Remote Center Compliance Device- a compliant robot wrist used to mate non compliant parts-developed by Draper Labs.
1976	Vision system and AL programming language are interfaced at Stanford by Bolles.
1976	HARPY speech understanding system completed at Carnegie Mellon by Reddy.
1977	AL-Stanford Robot Programming Language-completed by Schamano and Taylor.
1977(?)	Vision module developed at Stanford Research Institute commercialized by Machine Intelligence Corp.
1977	General Motors issues specification for a Programmable Universal Machine for Assembly-the PUMA robot.
1977	Unimation acquires Vicarm. Unimation wins PUMA bid.
1977(?)	ASEA commercializes a microprocesser controlled robot.
1977	Olivetti develops Sigma robot.
1978	First PUMA prototype, based on Scheinman's MIT model arm, is shipped to GM.
1978	Improved version of the RCC device developed by Draper Labs.
1979	First version of ACRONYM- a vision system using "reasoning about geometry" developed at Stanford.
1980	The Robotics Institute at Carnegie Mellon officially opens. It soon becomes the largest academic robot lab in the US
1980	First robot to pick randomly stacked connecting rods out of a bin developed at the University of Rhode Island.
1980	Mobile robot which could move through a simple obstacle course developed by Moravec at Stanford.
1981	Direct drive manipulator using rare earth motors- eliminating mechanical linkages. developed at Carnegie Mellon by Asada and Kanede.

1981 PUMA mounted on a microprocessor controlled omni direction mobile base demonstrated by Unimation.

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